Multipurpose Heat-Exchanger Networks for Heat Integration Across Plants

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The synthesis of multipurpose heat-exchanger networks that are capable of operating two plants stand-alone as well as integrated is presented. Designs for direct integration using process streams and indirect integration using intermediate-fluid circuits are obtained. The mathematical models proposed in the synthesis of these designs account for unassisted and assisted forms of integration, and they rely on results previously obtained in a targeting phase. Finally, an economic comparison between the two types of integration for a realistic case of a crude unit and a FCC unit is performed. The analysis also reveals that the widely accepted statement that indirect integration using steam can achieve most of the energy savings in the total site is not valid when compared with an intermediate-fluid circuit.

1. Introduction

Heat integration across plants, i.e., involving streams from different plants in a complex, has been used in practice. Nevertheless, some practitioners consider this type of integration impractical. Among the arguments used is the fact that the plants are physically separated and pumping and piping costs are high. The fact that the plants have different start-up and shutdown schedules is another reason. Thus, 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 also may operate at different production rates or depart from design conditions and, hence, need additional exchangers to reach desired operating temperatures. This integration can be accomplished directly, by using process streams, or indirectly, by using intermediate fluids, such as steam or dowtherms. Even though heat integration between plants has been attempted in practice, all of the discouraging aspects of the problem persuaded researchers and practitioners to leave opportunities for heat integration across plants unexplored.

The recovery of energy through integration between processes was first studied by Morton and Linnhoff,[1] who considered the overlap of grand composite curves to show the maximum possible heat recovery using steam. Later, Ahmad and Hui[2] extended this concept to direct and indirect heat integration. In addition, they proposed a systematic approach to generate different heat recovery schemes for interprocess integration. The concept of "Total Site" was introduced by Dhole and Linnhoff[3] to describe a set of processes serviced by and linked through a central utility system. In a recent paper, Rodera and Bagajewicz[4] discussed the opportunities for direct and indirect integration for two plants and proposed methods to assess the energy savings that can be accomplished using intermediate fluids. A methodology was presented to determine the minimum number of intermediate-fluid circuits needed to achieve maximum energy savings. Finally, this work was extended to the total site by Bagajewicz and Rodera.[5] While all of these studies determine the target energy savings, there is still a need to determine a heat-exchanger network that can accomplish minimum energy consumption when the plants are integrated as well as when they are functioning separately. This must take place at a minimum investment cost. The problem is also constrained by the fact that the same heat-exchanger network should operate satisfactorily for a stand-alone plant as well as when it is integrated.

Ahmad and Hui[2] proposed the overlapping of grand composite curves for targeting and discussed the use of mathematical programming to address the integration. They proposed a modification of the objective function used in the transshipment model[6] by considering weighting factors for those matches that are established between plants. However, they only mention the limitations of the model in predicting cyclic matches and do not further analyze the complications that arise in the construction of the heat-exchanger networks. In addition, they do not guarantee the flexibility of each plant during stand-alone operation.

In this paper, the energy savings targets identified[4] are employed in the synthesis of multipurpose heat-exchanger networks that are capable of operating each plant stand-alone as well as both plants integrated. Several mathematical programming models are presented for the design of these multipurpose heat-exchanger networks. The proposed models feature maximum energy recovery, which is obtained in the targeting phase, and a minimum number of units for both direct and indirect heat integration. These models also consider unassisted and assisted forms of integration. In addition, the heat recovery approach temperature (HRAT) and the exchanger minimum approach temperature (EMAT) are equal. Although better heat-exchanger models can be used, the simplicity of models featuring maximum energy recovery and the minimum number of units allows the discussion of the complexity of the problem in a more straightforward fashion. We

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Table 1. Target Energy Savings

scenario	example 1	example 2	example 3
direct integration	107.5 kW	104.5 kW	15.1 MW
indirect integration	107.5 kW	65.3 kW	13.9 MW
one intermediate-fluid circuit	107.5 kW	51.6 kW	12.6 MW
two intermediate-fluid circuits		65.3 kW	13.9 MW

believe that these new models can be obtained using existing approaches for designing heat-exchanger networks for single plants. Three examples are considered for which energy savings targets were calculated in a previous article.[4] The first two examples show the integration of small problems taken from literature. The third example is an integration of a crude unit and an FCC plant. Finally, an economical analysis of this last example is introduced to compare direct integration using the crude stream and indirect integration using an intermediate-fluid circuit.

2. Target Energy Savings

In this section, we briefly review the conclusions of the targeting procedures presented in an earlier paper.[4]

(a) Energy savings across plants are effectively accomplished by transferring heat between plant pinch temperatures.

(b) An LP model to determine the maximum energy savings that can be achieved by transferring heat from one plant to the other between pinch temperatures is presented. Flexibility for the design of multipurpose heat-exchanger networks is a consequence of the degenerate solutions to this problem.

(c) The existence of assisted heat transfer, omitted by other researchers, is emphasized. This assisted heat transfer consists of transferring heat above or below the zone between pinch temperatures, which is needed to enable maximum heat transfer between pinch temperatures.

(d) For indirect integration, a procedure is presented to evaluate the feasibility of a single circuit to achieve maximum energy savings.

(e) An MILP model is presented and solved to determine the location of a single circuit. Then the model is extended to multiple circuits to include the case in which a single circuit is not capable of realizing maximum energy savings.

The following three examples will be used in this article and are taken from Rodera and Bagajewicz:[4] example 1—test case #2 (L&H) from Linnhoff and Hindmarsh[7] as plant 1 and problem 4sp1 as plant 2; example 2—a problem from Trivedi[8] is plant 1 and example 1 from Ciric and Floudas[9] is plant 2; example 3—a crude unit processing 150 000 bbl/day and an FCC plant processing 40 000 bbl/day, in which the crude unit is plant 1 and the FCC unit is plant 2.

The energy savings obtained in the different integration scenarios for these examples are reported in Table 1.

In example 1, maximum energy savings can be accomplished using either direct or indirect heat integration. In the case of indirect integration, the use of a single intermediate-fluid circuit between pinch temperatures guarantees the transfer of the total heat target amount. Therefore, this is an example of an unassisted heat-transfer case. There are different targeting solutions, due to problem degeneracy, leading to different possible ways of implementing the intermediate-fluid circuit. Higher and lower circuit solutions (defined by Rodera and Bagajewicz[4]) can be obtained by algorithmic methods.

Example 2 shows the instance of an assisted heat-integration case. Direct integration requires the transference of assisting heat in the region above both pinch temperatures to attain maximum energy savings by transferring between pinch temperatures. Because of a gap resulting from the shifts in the temperature scales, the heat amount that plant 1 can receive is reduced. Therefore, indirect integration accomplishes lower energy savings when compared to direct integration. A single intermediate-fluid circuit in the zone between pinch temperatures is not capable of transferring all of the maximum possible heat for indirect integration. This limitation is removed by adding another intermediate-fluid circuit in the zone above pinch temperatures.

In the third example, direct integration can attain larger energy savings because for indirect integration the region between pinch temperatures is reduced to make the use of an intermediate-fluid circuit possible. The use of a single intermediate-fluid circuit can transfer up to 91% of the total energy savings possible for indirect integration. Two degenerate solutions were identified. They provide flexibility in the selection of the intermediate-fluid flow rate. Total energy savings can be achieved by the implementation of a system of two intermediate-fluid circuits.

3. Multipurpose Heat-Exchanger Networks

The design of multipurpose heat-exchanger networks is now considered. An extension of the "minimum matching approach"[6] is developed to obtain the minimum number of matches for the system and to translate this result to a network with the minimum number of heat exchangers. The transshipment model that finds the minimum number of matches among a set of streams has the advantage of being simple and computationally tractable. This model has limitations: global optimality is not attained because the HRAT and EMAT are equal. Gundersen and Grossmann[10] mention the need for differentiating between the various heat-exchanger network structures that can be obtained after the transshipment model is solved. We acknowledge the limitation of our models, which were selected as a first approximation to show the interaction between two plants when a multipurpose heat-exchanger network is designed. Although desired, the complexity of more elaborate models would obscure the intricacies of the multipurpose design problem being attempted.

3.1. Additive Heat Exchanger Networks. Assume, for example, that the targeting procedure has revealed opportunities for indirect integration using an intermediate-fluid stream that collects heat from plant 2 and delivers it to plant 1. The demands for both the heating utility of plant 1 and the cooling utility of plant 2 are reduced. Consider now the network of Figure 1a. It corresponds to a subset of matches of two nonintegrated plants. If one wants to preserve the existing structure, new heat exchangers should be added to obtain the network for the integrated operation. Thus, for the case of Figure 1a, the addition of two new exchangers is proposed (Figure 1b).

This suggests the following definition:

An additive multipurpose heat-exchanger network is one in which the heat exchangers matching hot and cold

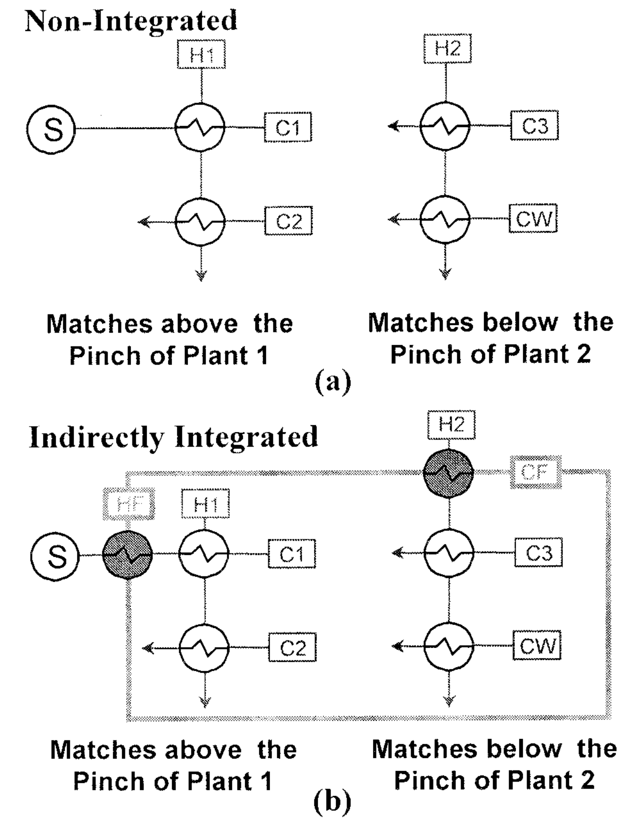

Figure 1. Additive heat-exchanger networks.

streams belonging to the plant under consideration are present in both stand-alone and across-plants integration, and they exchange heat between the same streams. Heat exchangers used for any type of integration, direct or not, are new heat exchangers.

3.2. Classification of Stream Matches. With the purpose of gaining a better understanding of the different possible matching schemes in the condition of integration and stand-alone operation for the system of two plants, a description of different structures with stream matches follows. Consider the case of hot stream i and cold stream j in plant 1 in the region above the combined-plant pinch temperature. Let k correspond to some hot stream used for heat integration between plants, either an intermediate-fluid stream or a hot stream from plant 2. Table 2 shows the different matching possibilities in nonintegrated and integrated cases.

Case 1 indicates that the match (i,j) is present in both situations. The second case accounts for the match (i,j) not present in the integrated case, with stream j exchanging heat with some other hot stream from plant 2 instead. Case 3 indicates that a new match is added to stream j. The next three cases account for a match not being present in one of the networks. Finally, the last case indicates that both matches are present in the integrated plant, while the match (i,j) is not present in the nonintegrated plant. Similar situations arise if plant 2 is considered.

Cases 1 or 3 in Table 2 are situations arising in additive multipurpose heat-exchanger networks. In these additive networks, it is possible to find cases in which some of the heat exchangers have zero heat loads in one of the modes of operation (cases 2 and 4). Finally, cases 5−7 are also situations found in additive networks. Networks in which, to differentiate from additive multipurpose heat-exchanger networks, the same heat exchanger can be used for different purposes will be discussed later.

3.3. Effect of the Combined-Plant Pinch Temperature. The direct application of the transshipment model of Papoulias and Grossmann[6] to a single plant requires pinch decomposition to predict correctly the minimum number of matches above and below the pinch temperature. Heat-exchanger network design with EMAT equal to HRAT and based on pinch decomposition follows. This design reflects a minimum number of units at either side of the pinch temperature. Elimination of this decomposition[11] and use of an EMAT lower than HRAT[10] usually leads to a lower total number of matches for the entire network. For simplicity, the analysis of the problem presented in this paper considers the pinch decomposition case to show the interaction between the heat-exchanger networks of two plants. Therefore, to distinguish among plant regions in the heat cascade diagram that are obtained after pinch decomposition, the subscript r is used. Values $r = u_1/u_2$ correspond to regions above the pinch temperature, and values $r = l_1/l_2$ correspond to regions below the pinch temperature. These regions are depicted in Figure 2.

Further partition of the system is required when maximum possible energy savings are implemented during direct or indirect integration, because a combined-plant pinch temperature appears. For the case in which the combined-plant pinch temperature falls between the plant pinch temperatures,[4] four regions are possible, as illustrated in Figure 2. Special cases in which the combined-plant pinch temperature is located above or below both plant pinch temperatures are similar and can be derived easily from the study of the more common case of a combined-plant pinch temperature falling between pinch temperatures.

To distinguish regions in which indirect/direct heat transfer across plants takes place, new values of the subscript r are used. Values $r = \mathrm{e_u}$ and $r = \mathrm{e_l}$ correspond to the regions immediately above and below the combined-plant pinch temperature. These regions span between pinch temperatures and are those in which heat that leads to energy savings is effectively transferred. In turn, the values $r = \mathrm{a}$ and $r = \mathrm{b}$ correspond to the regions above and below both pinch temperatures in which assisting heat transfer takes place (Figure 2).

The decomposition employed in the design of the multipurpose heat-exchanger network may lead to the use of two heat-exchanger units between the same pair of streams of a single plant at both sides of the combined-plant pinch temperature. A single unit is needed in this case if a design for the single plant is conducted. This is a limitation of the present method, and it can be ameliorated using other methods in which EMAT is smaller or energy relaxation takes place.

3.4. Sets and Constraints. For convenience, several general sets are defined (see Nomenclature under Stand-alone plants and Integration across plants).

Consider the constraints used by Papoulias and Grossmann[6] in their transshipment model for the minimum number of stream matches. The left-hand side of these constraints is rewritten using a compact notation as follows:

Equations

$$\mathbf{B}_{\mathrm{T}}\mathbf{(}S_r,\hat{S}_r,D_r,\hat{D}_r,N_r\mathbf{)} = \begin{bmatrix} \delta_{it}^{\mathrm{T}} - \delta_{i(t-1)}^{\mathrm{T}} + \sum_{j\in D_t\subset D_r} V_{ijt}^{\mathrm{T}} + \sum_{k\in \hat{D}_t\subset \hat{D}_r} V_{ikt}^{\mathrm{T}} - W_{it}^{\mathrm{H}} \\ \qquad \forall\, i \in S_t \subset S_r \qquad \forall\, t \in N_r \\ \sum_{i\in S_t\subset S_r} V_{ijt}^{\mathrm{T}} + \sum_{k\in \hat{S}_t\subset \hat{S}_r} V_{kjt}^{\mathrm{T}} - W_{jt}^{\mathrm{C}} \\ \qquad \forall\, j \in D_t \subset D_r \qquad \forall\, t \in N_r \end{bmatrix} \quad (1)$$

Inequalities

$$\mathbf{G}_{\mathrm{T}}(S_r,\hat{S}_r,D_r,\hat{D}_r,N_r) = \begin{bmatrix} \sum_{t\in N_r} V_{ijt}^{\mathrm{T}} - U_{ijr}^{\mathrm{T}} Y_{ijr}^{\mathrm{T}} & \forall\, i \in S_r,\ \forall\, j \in D_r \\ \sum_{t\in \hat{N}_r} V_{kjt}^{\mathrm{T}} - U_{kjr}^{\mathrm{T}}\, Y_{kjr}^{\mathrm{T}} & \forall\, k \in \hat{S}_r,\ \forall\, j \in D_r \\ \sum_{t\in \hat{N}_r} V_{ikt}^{\mathrm{T}} - U_{ikr}^{\mathrm{T}}\, Y_{ikr}^{\mathrm{T}} & \forall\, i \in S_r,\ \forall\, j \in D_r \\ -\delta_{it}^{\mathrm{T}} & \forall\, i \in S_t \subset S_r \quad \forall\, t \in N \\ -V_{ijt}^{\mathrm{T}} & \forall\, i \in S_t \subset S_r,\ \forall\, j \in D_t \subset D_r \quad \forall\, t \in N \\ -V_{kjt}^{\mathrm{T}} & \forall\, k \in \hat{S}_t \subset \hat{S}_r,\ \forall\, j \in D_t \subset D_r \quad \forall\, t \in N \\ -V_{ikt}^{\mathrm{T}} & \forall\, i \in S_t \subset S_r,\ \forall\, k \in \hat{D}_t \subset \hat{D} \quad \forall\, t \in N \end{bmatrix} \quad (2)$$

Binary Variables

$$\mathbf{I}_{\mathrm{T}}\mathbf{(}S_r,\hat{S}_r,D_r,\hat{D}_r\mathbf{)} = \begin{bmatrix} Y_{ijr}^{\mathrm{T}} & \forall\, i \in S_r,\ \forall\, j \in D_r \\ Y_{kjr}^{\mathrm{T}} & \forall\, k \in \hat{S}_r,\ \forall\, j \in D_r \\ Y_{ikr}^{\mathrm{T}} & \forall\, i \in S_r,\ \forall\, k \in \hat{D}_r \end{bmatrix} \quad (3)$$

where the script T denotes the type of integration considered. These types are T = (I) no integration across plants, T = (II) indirect integration across plants using intermediate-fluid circuits, and T = (III) direct integration across plants.

Notice that extra terms are added to the balances in eq 1 to consider not only heat transfer within the individual plants but also heat that is used for integration across plants. Moreover, separated constraints are written in eqs 2 and 3 to account for the different stream matches. Finally, the specific sets that are included in the general sets previously defined are in Nomenclature under Single Plant and Intermediate-Fluid Circuits.

3.5. Mathematical Model for Single Plant Integration. On the basis of the general constraints defined above, the transshipment model minimizing the number of matches[6] can be expressed in the following compact form.

$$\mathrm{P1} = \min \sum_{i\in H_r^p, j\in C_r^p; r = u_p, l_p; p = 1,2} Y_{ijr}^{\mathrm{I}} \quad (4)$$

subject to (s.t.)

$$\left.\begin{cases} \mathbf{B}_{\mathrm{I}}\mathbf{(}H_r^p,\varnothing,C_r^p,\varnothing,N_r^p\mathbf{)} = 0 \\ \mathbf{G}_{\mathrm{I}}\mathbf{(}H_r^p,\varnothing,C_r^p,\varnothing,N_r^p\mathbf{)} \le 0 \\ \mathbf{I}_{\mathrm{I}}\mathbf{(}H_r^p,\varnothing,C_r^p,\varnothing\mathbf{)} = \{0,1\} \end{cases}\right\} r = u_p,\ l_p \qquad p = 1,2 \quad (5)$$

Note that as no integration is considered, the supplementary sets $\hat{S}_r$, $\hat{D}_r$, and $\hat{N}_r$ are empty. Moreover, problem P1 is separable by construction, i.e., four separate problems can be considered with each of them accounting for a single plant region.

Table 2. Matching Possibilities

CASE NUMBER	MATCHES IN PLANT 1	
	NONINTEGRATED	INTEGRATED
1	(i,j)	(i,j)
2	(i,j)	(k,j)
3	(i,j)	(i,j) and (k,j)
4	(i,j)	
5		(i,j)
6		(k,j)
7		(i,j) and (k,j)

3.6. Mathematical Models for Indirect Heat Integration. The shift of scales used in the targeting procedure is not needed, because each plant can be solved independently. Moreover, the intermediate-fluid streams may create interval partitions when they are included in the corresponding intervals by using their initial temperatures. These temperatures were determined previously by the targeting procedures.

3.6.1. Heat-Sink Plant. The following model is presented to obtain the minimum number of matches required during the integrated state by restricting the solution to additive heat-exchanger networks:

$$\mathrm{P2}_1 = \min\{ \sum_{i\in H^1_{a\oplus e_u}\cup H^F_{e_u},\ j\in C^1_{a\oplus e_u}\cup C^F_a} Y_{ijr}^{\mathrm{II}} + \sum_{i\in H^1_{e_l}\cup H^F_{e_l},\ j\in C^1_{e_l}} Y_{ijr}^{\mathrm{II}} + \sum_{i\in H^1_b,\ j\in C^1_b\cup C^F_b} Y_{ijr}^{\mathrm{II}} \} \quad (6)$$

s.t.

$$\left.\begin{cases} \mathbf{B}_{\mathrm{I}}(H_r^1,\varnothing,C_r^1,\varnothing,N_r) = 0 \\ \mathbf{G}_{\mathrm{I}}(H_r^1,\varnothing,C_r^1,\varnothing,N_r) \le 0 \\ \mathbf{I}_{\mathrm{I}}(H_r^1,\varnothing,C_r^1,\varnothing\mathbf{)} = \{0,1\} \end{cases}\right\} r = \mathrm{a} \oplus \mathrm{e_u},\ \mathrm{e_l},\ \mathrm{b} \quad (7)$$

$$\begin{Bmatrix} \mathbf{B}_{\mathrm{II}}(H^1_{a\oplus e_u}\cup H^F_{e_u},\varnothing,C^1_{a\oplus e_u}\cup C^F_a,\varnothing,N_{a\oplus e_u}) = 0 \\ \mathbf{G}_{\mathrm{II}}(H^1_{a\oplus e_u}\cup H^F_{e_u},\varnothing,C^1_{a\oplus e_u}\cup C^F_a,\varnothing,N_{a\oplus e_u}) \le 0 \\ \mathbf{I}_{\mathrm{II}}(H^1_{a\oplus e_u}\cup H^F_{e_u},\varnothing,C^1_{a\oplus e_u}\cup C^F_a,\varnothing) = \{0,1\} \\ \mathbf{B}_{\mathrm{II}}(H^1_{e_l}\cup H^F_{e_l},\varnothing,C^1_{e_l},\varnothing,N_{e_l}) = 0 \\ \mathbf{G}_{\mathrm{II}}(H^1_{e_l}\cup H^F_{e_l},\varnothing,C^1_{e_l},\varnothing,N_{e_l}) \le 0 \\ \mathbf{I}_{\mathrm{II}}(H^1_{e_l}\cup H^F_{e_l},\varnothing,C^1_{e_l},\varnothing) = \{0,1\} \\ \mathbf{B}_{\mathrm{II}}(H^1_b,\varnothing,C^1_b\cup C^F_b,\varnothing,N_b) = 0 \\ \mathbf{G}_{\mathrm{II}}(H^1_b,\varnothing,C^1_b\cup C^F_b,\varnothing,N_b) \le 0 \\ \mathbf{I}_{\mathrm{II}}(H^1_b,\varnothing,C^1_b\cup C^F_b,\varnothing) = \{0,1\} \end{Bmatrix} \quad (8)$$

$$\mathbf{I}_{\mathrm{II}}(H_r^1,\varnothing,C_r^1,\varnothing) \ge \mathbf{I}_{\mathrm{I}}(H_r^1,\varnothing,C_r^1,\varnothing) \qquad r = \mathrm{a} \oplus \mathrm{e_u},\ \mathrm{e_l},\ \mathrm{b} \quad (9)$$

The set of constraints 7 corresponds to the heat-sink plant (plant 1) in conditions of no integration, while set 8 corresponds to the plant operating in the integrated state with the intermediate-fluid streams present in the corresponding heat-transfer regions. Notice that the supplementary sets $\hat{S}_r$, $\hat{D}_r$, and $\hat{N}_r$ are empty because the intermediate-fluid streams are added to the respective hot and cold stream sets in the corresponding regions of heat transfer across plants. Finally, constraint 9 requires that matches existing during stand-alone operation also are present during integration. This last constraint conveys the basic concept of an additive heat-exchanger network. Because one set of constraints is included in the other, the objective function counts the matches for the integrated case only.

3.6.2. Heat-Source Plant. The model is similar to the case of the heat-sink plant and is presented without further explanation.

$$P2_2 = \min\{ \sum_{i \in H^2_a \cup H^F_a,\, j \in C^2_a} Y^{II}_{ijr} + \sum_{i \in H^2_{e_u},\, j \in C^2_{e_u} \cup C^F_{e_u}} Y^{II}_{ijr} + \sum_{i \in H^2_{e_l \oplus b} \cup H^F_b,\, j \in C^2_{e_l \oplus b} \cup C^F_{e_l}} Y^{II}_{ijr} \} \quad (10)$$

s.t.

$$\left\{ \begin{array}{l} \mathbf{B}_I(H^2_r, \emptyset, C^2_r, \emptyset, N_r) = 0 \\ \mathbf{G}_I(H^2_r, \emptyset, C^2_r, \emptyset, N_r) \le 0 \\ \mathbf{I}_I(H^2_r, \emptyset, C^2_r, \emptyset) = \{0,1\} \end{array} \right\} r = \text{a, e}_u\text{, e}_l \oplus \text{b} \quad (11)$$

$$\left\{ \begin{array}{l} \mathbf{B}_{II}(H^2_a \cup H^F_a, \emptyset, C^2_a, \emptyset, N_a) = 0 \\ \mathbf{G}_{II}(H^2_a \cup H^F_a, \emptyset, C^2_a, \emptyset, N_a) \le 0 \\ \mathbf{I}_{II}(H^2_a \cup H^F_a, \emptyset, C^2_a, \emptyset) = \{0,1\} \\ \mathbf{B}_{II}(H^2_{e_u}, \emptyset, C^2_{e_u} \cup C^F_{e_u}, \emptyset, N_{e_u}) = 0 \\ \mathbf{G}_{II}(H^2_{e_u}, \emptyset, C^2_{e_u} \cup C^F_{e_u}, \emptyset, N_{e_u}) \le 0 \\ \mathbf{I}_{II}(H^2_{e_u}, \emptyset, C^2_{e_u} \cup C^F_{e_u}, \emptyset) = \{0,1\} \\ \mathbf{B}_{II}(H^2_{e_l \oplus b} \cup H^F_b, \emptyset, C^2_{e_l \oplus b} \cup C^F_{e_l}, \emptyset, N_{e \oplus b}) = 0 \\ \mathbf{G}_{II}(H^2_{e_l \oplus b} \cup H^F_b, \emptyset, C^2_{e_l \oplus b} \cup C^F_{e_l}, \emptyset, N_{e \oplus b}) \le 0 \\ \mathbf{I}_{II}(H^2_{e_l \oplus b} \cup H^F_b, \emptyset, C^2_{e_l \oplus b} \cup C^F_{e_l}, \emptyset) = \{0,1\} \end{array} \right\} \quad (12)$$

$$\mathbf{I}_{II}(H^2_r, \emptyset, C^2_r, \emptyset) \ge \mathbf{I}_I(H^2_r, \emptyset, C^2_r, \emptyset) \qquad r = \text{a, e}_u\text{, e}_l \oplus \text{b} \quad (13)$$

3.7. Idle Heat Exchangers. The use of inequality 9 in problem $P2_1$ and inequality 13 in problem $P2_2$ makes it possible for some of the heat exchangers to become idle in the integrated mode of operation. Whenever a match between two streams is included in the stand-alone integration, the constraints also require it to be present in the integrated mode. Then, instances of case 1 already have been considered. However, the models cannot represent instances of case 4 because a match is not allowed to be absent from the integrated mode when it is present in the stand-alone mode. Thus, the only possibility for case 4 to occur is when the exchanger not required is idle during the integrated mode of operation. Therefore, case 4 is contained in case 1. The same can be said of case 3, which includes case 2 and leads to the presence of an idle exchanger whenever case 2 takes place.

Given the additive nature of models $P2_1$ and $P2_2$, the situation represented by cases 5 and 7 results in the existence of unnecessary exchangers in the stand-alone mode. These exchangers will then be idle during this mode of operation. Finally, case 6 represents the purely additive case. The possibility of reducing the number of heat exchangers by identifying exchangers that become idle in one of the modes of operations and assigning them to some other matches are explored later.

3.8. Heat Loops. Consider now the situation depicted by Figure 3a, in which part of the network of plant 1

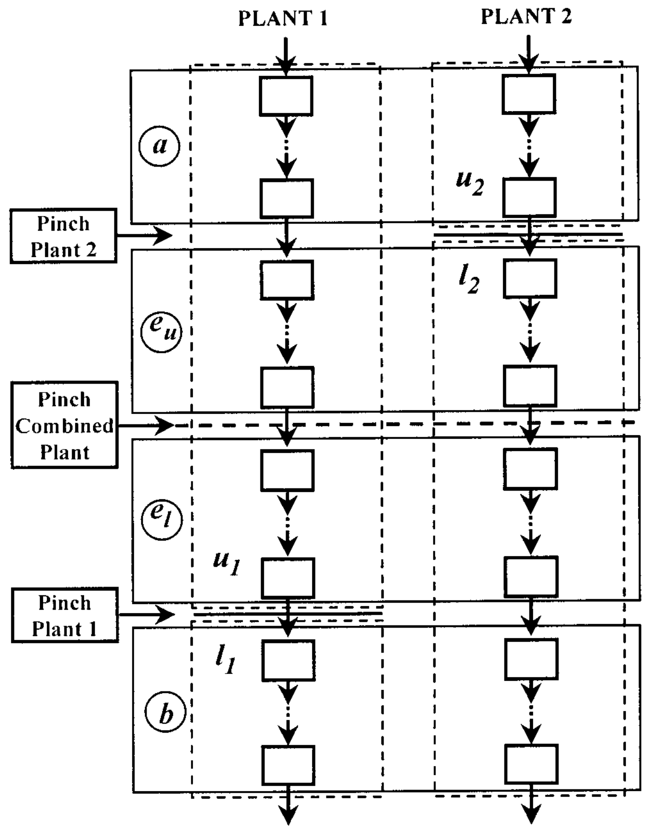

Figure 2. Heat transfer regions for two plants.

above the combined-plant pinch temperature revealing opportunities for integration is presented. The corresponding solution for the indirect integration with plant 2 requires the addition of two exchangers (Figure 3b). The first exchanger (E4) is between hot stream H2 and cold stream C1 and represents a new match that uses hot and cold streams belonging to plant 1 (case 5). The second new exchanger (E5) is between the intermediate-fluid stream and cold stream C2. Exchangers E3 and E5 correspond to case 3. The heat transfer in these exchangers is sufficient to fulfill the heating demand of cold stream C2. Therefore, exchanger E2, which is necessary when plant 1 works in stand-alone mode, is no longer required during integration (case 4).

The application of the concept of additive heat-exchanger networks using model $P2_1$ for plant 1 is shown in Figure 3c. The result is the direct addition of exchangers E4 and E5 to the original network of plant 1. A heat loop involving exchangers E1, E2, E3, and E4 has been established. The existence of this loop has the advantage that the heat can be accommodated through these exchangers such that the overall cost is minimal. That is, exchanger E2 can still be used during integration to fulfill part of the heat demand of stream C2 if the load on exchanger E3 is reduced and the load on exchanger E4 is increased. In the case of exchanger E4, its use would result from a decrease in the load on exchanger E2 and an increase in the load on exchanger E3. On the other hand, one could choose to leave exchangers E2 or E4 idle so that cleaning can be performed on them when they are not in use. However, models $P2_1$ and $P2_2$ do not favor one solution or the other. This leads to a modification of the objective function discussed in the next section.

3.9. Loop Elimination. To guarantee the identification of the exchangers that are not required in one mode

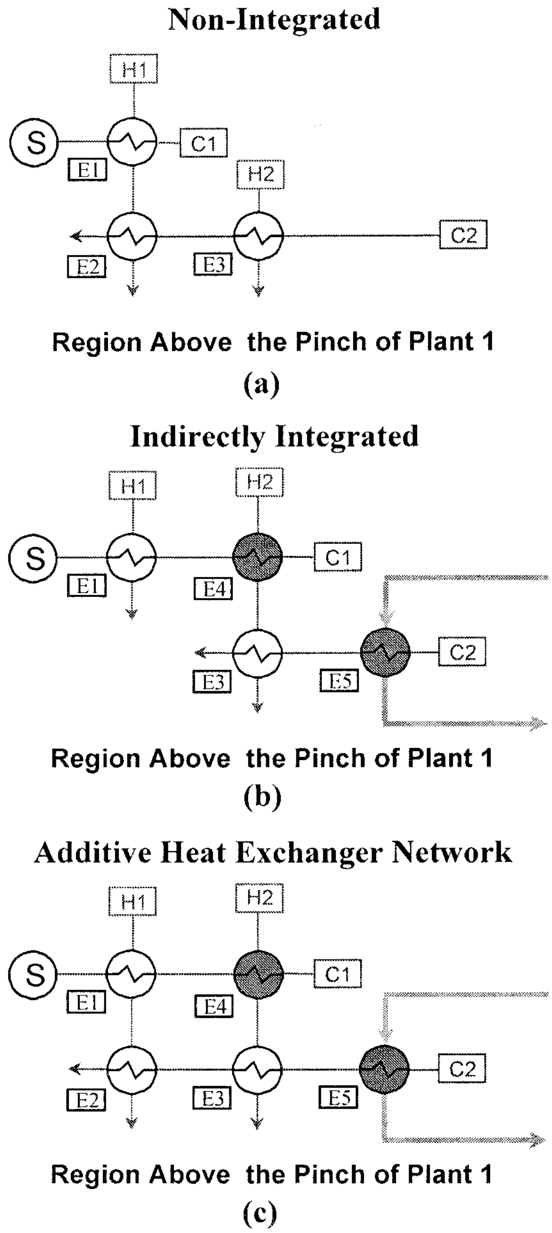

Figure 3. Heat loops.

of operation (i.e., they can become idle without influencing operation), changes in the objective function and constraints of models $P2_1$ and $P2_2$ are necessary. For cases presenting a loop such as the one shown in Figure 3c, this identification is equivalent to the elimination of the loop in each of the integration conditions.

Consider first the case in which an exchanger used during integration can become idle when the plants are working independently. The objective function used in model $P2_1$ counts only the matches used during integration. The following modification of this function prevents matches only existing for integration purposes from transferring heat in the nonintegrated case.

$$\min\Big\{ \sum_{i\in H^1_{a\oplus e_u}\cup H^F_{e_u},\, j\in C^1_{a\oplus e_u}\cup C^F_a} Y^{II}_{ijr} + \sum_{i\in H^1_{e_l}\cup H^F_{e_l},\, j\in C^1_{e_l}} Y^{II}_{ijr} + \sum_{i\in H^1_b,\, j\in C^1_b\cup C^F_b} Y^{II}_{ijr} + \epsilon \sum_{i\in H^1_r,\, j\in C^1_r;\, r=a\oplus e_u,e_l,b} Y^{I}_{ijr} \Big\} \quad (14)$$

This new objective function not only counts the matches for the integrated case, but also counts the ones required for independent integration. A weighting factor, ϵ, is introduced (0.01, for example), which is small enough to make this last term smaller than one. Therefore, this objective function makes possible the identification of idle exchangers (only used during conditions of integration). The modification in the objective function previously presented does not guarantee the elimination of heat loops during conditions of integration because all stand-alone operation matches are forced to exist when the plants are integrated by constraints 9 and 13. Thus, an additional modification is needed. A new binary variable Z^T_{ijr} is defined that plays the same role as Y^T_{ijr} but is not restricted by the use of constraints 9 and 13. The following additional constraints are also introduced:

Additional Inequalities

$$\mathbf{A}_T(S_r,D_r,N_r) = \begin{bmatrix} \sum_{t\in N_r} V^T_{ijt} - U^T_{ijr}\, Z^T_{ijr} \quad \forall\, i \in S_r,\ \forall\, j \in D_r \\ L^T_{ijr}\, Z^T_{ijr} - \sum_{t\in N_r} V^T_{ijt} \quad \forall\, i \in S_r,\ \forall\, j \in D_r \end{bmatrix} \quad (15)$$

Additional Binary Variables

$$\mathbf{Z}_T(S_r,D_r) = [Z^T_{ijr}\ \forall\, i \in S_r,\ \forall\, j \in D_r] \quad (16)$$

Therefore, the models for indirect integration that identify idle heat exchangers in either of the modes of operation are as follows:

Heat-Sink Plant

$$P3_1 = \min\Big\{ \sum_{i\in H^1_{a\oplus e_u}\cup H^F_{e_u},\, j\in C^1_{a\oplus e_u}\cup C^F_a} Y^{II}_{ijr} + \sum_{i\in H^1_{e_l}\cup H^F_{e_l},\, j\in C^1_{e_l}} Y^{II}_{ijr} + \sum_{i\in H^1_b,\, j\in C^1_b\cup C^F_b} Y^{II}_{ijr} + \epsilon \sum_{i\in H^1_r,\, j\in C^1_r;\, r=a\oplus e_u,e_l,b} (Y^{I}_{ijr} + Z^{II}_{ijr}) \Big\} \quad (17)$$

s.t.

constraints 7−9

$$\left\{ \begin{matrix} \mathbf{A}_{II}(H^1_r,C^1_r,N_r) \le 0 \\ \mathbf{Z}_{II}(H^1_r,C^1_r) = 0,1 \end{matrix} \right\} r = a \oplus e_u,\ e_l,\ b \quad (18)$$

Heat-Source Plant

$$P3_2 = \min\Big\{ \sum_{i\in H^2_a\cup H^F_a,\, j\in C^2_a} Y^{II}_{ijr} + \sum_{i\in H^2_{e_u},\, j\in C^2_{e_u}\cup C^F_{e_u}} Y^{II}_{ijr} + \sum_{i\in H^2_{e_l\oplus b}\cup H^F_b,\, j\in C^2_{e_l\oplus b}\cup C^F_{e_l}} Y^{II}_{ijr} + \epsilon \sum_{i\in H^2_r,\, j\in C^2_r;\, r=a,e_u,e_l\oplus b} (Y^{I}_{ijr} + Z^{II}_{ijr}) \Big\} \quad (19)$$

s.t.

constraints 11−13

$$\left\{ \begin{matrix} \mathbf{A}_{II}(H^2_r,C^2_r,N_r) \le 0 \\ \mathbf{Z}_{II}(H^2_r,C^2_r) = 0,1 \end{matrix} \right\} r = a,\ e_u,\ e_l \oplus b \quad (20)$$

The use of the new binary variable serves the purpose of avoiding the consideration of matches not required during integration that nevertheless exist because of the inclusion of constraints 9 or 13. Models $P3_1$ and $P3_2$ are used in this paper.

Instead of solving models $P3_1$ or $P3_2$, an alternative two-step procedure can be implemented without the need of the small parameter ϵ. One can first minimize the total number of matches used in conditions of integration (models $P2_1$ and $P2_2$) and obtain values for the binary variables Y_{ijr}^{II}. One can now use the same constraints as in $P3_1$ and $P3_2$, fix the binary variables Y_{ijr}^{II} to the values found in the first step and minimize the summation of the binary variables Y_{ijr}^{I} and Z_{ijr}^{II}.

3.10. Mathematical Model for Direct Heat Integration. The model for direct integration that minimizes the number of matches and identifies exchangers that become idle during one of the modes of operation is presented.

$$P4 = \min\{ \sum_{i\in H_r^1,\, j\in C_r^1;\, r=\mathrm{a}\oplus\mathrm{e_u},\mathrm{e_l},\mathrm{b}} Y_{ijr}^{\mathrm{III}} + \sum_{i\in H_r^2,\, j\in C_r^2;\, r=\mathrm{a},\mathrm{e_u},\mathrm{e_l}\oplus\mathrm{b}} Y_{ijr}^{\mathrm{III}} + \sum_{i\in H_r^2,\, j\in C_r^1;\, r=\mathrm{e_u},\mathrm{e_l}} Y_{ijr}^{\mathrm{III}} + \sum_{i\in H_r^1,\, j\in C_r^2;\, r=\mathrm{a},\mathrm{b}} Y_{ijr}^{\mathrm{III}} + \epsilon \sum_{i\in H_r^1,\, j\in C_r^1;\, r=\mathrm{a}\oplus\mathrm{e_u},\mathrm{e_l},\mathrm{b}} (Y_{ijr}^{\mathrm{I}} + Z_{ijr}^{\mathrm{III}}) + \sum_{i\in H_r^2,\, j\in C_r^2;\, r=\mathrm{a},\mathrm{e_u},\mathrm{e_l}\oplus\mathrm{b}} (Y_{ijr}^{\mathrm{I}} + Z_{ijr}^{\mathrm{III}})\} \quad (21)$$

s.t.

constraints 7 and 11

$$\left\{\begin{array}{l} \mathbf{B}_{\mathrm{III}}(H^1_{\mathrm{a}\oplus\mathrm{e_u}},H^2_{\mathrm{e_u}},C^1_{\mathrm{a}\oplus\mathrm{e_u}},C^2_{\mathrm{a}},N_{\mathrm{a}\oplus\mathrm{e_u}}) = 0 \\ \mathbf{G}_{\mathrm{III}}(H^1_{\mathrm{a}\oplus\mathrm{e_u}},H^2_{\mathrm{e_u}},C^1_{\mathrm{a}\oplus\mathrm{e_u}},C^2_{\mathrm{a}},N_{\mathrm{a}\oplus\mathrm{e_u}}) \le 0 \\ \mathbf{I}_{\mathrm{III}}(H^1_{\mathrm{a}\oplus\mathrm{e_u}},H^2_{\mathrm{e_u}},C^1_{\mathrm{a}\oplus\mathrm{e_u}},C^2_{\mathrm{a}}) = \{0,1\} \\ \mathbf{B}_{\mathrm{III}}(H^1_{\mathrm{e_l}},H^2_{\mathrm{e_l}},C^1_{\mathrm{e_l}},\emptyset,N_{\mathrm{e_l}}) = 0 \\ \mathbf{G}_{\mathrm{III}}(H^1_{\mathrm{e_l}},H^2_{\mathrm{e_l}},C^1_{\mathrm{e_l}}\emptyset,N_{\mathrm{e_l}}) \le 0 \\ \mathbf{I}_{\mathrm{III}}(H^1_{\mathrm{e_l}},H^2_{\mathrm{e_l}},C^1_{\mathrm{e_l}},\emptyset) = \{0,1\} \\ \mathbf{B}_{\mathrm{III}}(H^1_{\mathrm{b}},\emptyset,C^1_{\mathrm{b}},\emptyset,N_{\mathrm{b}}) = 0 \\ \mathbf{G}_{\mathrm{III}}(H^1_{\mathrm{b}},\emptyset,C^1_{\mathrm{b}},C^2_{\mathrm{b}},N^1_{\mathrm{b}}) \le 0 \\ \mathbf{I}_{\mathrm{III}}(H^1_{\mathrm{b}},\emptyset,C^1_{\mathrm{b}},C^2_{\mathrm{b}}) = \{0,1\} \end{array}\right\} \quad (22)$$

$$\left\{\begin{array}{l} \mathbf{B}_{\mathrm{III}}(H^2_{\mathrm{a}},H^1_{\mathrm{a}},C^2_{\mathrm{a}},\emptyset,N_{\mathrm{a}}) = 0 \\ \mathbf{G}_{\mathrm{III}}(H^2_{\mathrm{a}},H^1_{\mathrm{a}},C^2_{\mathrm{a}},\emptyset,N_{\mathrm{a}}) \le 0 \\ \mathbf{I}_{\mathrm{III}}(H^2_{\mathrm{a}},H^1_{\mathrm{a}},C^2_{\mathrm{a}},\emptyset) = \{0,1\} \\ \mathbf{B}_{\mathrm{III}}(H^2_{\mathrm{e_u}},\emptyset,C^2_{\mathrm{e_u}},C^1_{\mathrm{e_u}},N_{\mathrm{e_u}}) = 0 \\ \mathbf{G}_{\mathrm{III}}(H^2_{\mathrm{e_u}},\emptyset,C^2_{\mathrm{e_u}},C^1_{\mathrm{e_u}},N_{\mathrm{e_u}}) \le 0 \\ \mathbf{I}_{\mathrm{III}}(H^2_{\mathrm{e_u}},\emptyset,C^2_{\mathrm{e_u}},C^1_{\mathrm{e_u}}) = \{0,1\} \\ \mathbf{B}_{\mathrm{III}}(H^2_{\mathrm{e_l}\oplus\mathrm{b}},H^1_{\mathrm{b}},C^2_{\mathrm{e_l}\oplus\mathrm{b}},C^1_{\mathrm{e_l}},N^2_{\mathrm{e_l}\oplus\mathrm{b}}) = 0 \\ \mathbf{G}_{\mathrm{III}}(H^2_{\mathrm{e_u}\oplus\mathrm{b}},H^1_{\mathrm{b}},C^2_{\mathrm{e_l}\oplus\mathrm{b}},C^1_{\mathrm{e_l}},N_{\mathrm{b}}) \le 0 \\ \mathbf{I}_{\mathrm{III}}(H^2_{\mathrm{e_u}\oplus\mathrm{b}},H^1_{\mathrm{b}},C^2_{\mathrm{e_l}\oplus\mathrm{b}},C^1_{\mathrm{e_l}}) = \{0,1\} \end{array}\right\} \quad (23)$$

$$\left\{\begin{array}{l} \mathbf{A}_{\mathrm{III}}(H^1_r,C^1_r,N_r) \le 0 \\ \mathbf{Z}_{\mathrm{III}}(H^1_r,C^1_r) = 0,1 \end{array}\right\} r = \mathrm{a} \oplus \mathrm{e_u},\ \mathrm{e_l},\ \mathrm{b} \quad (24)$$

$$\left\{\begin{array}{l} \mathbf{A}_{\mathrm{III}}(H^2_r,C^2_r,N_r) \le 0 \\ \mathbf{Z}_{\mathrm{III}}(H^2_r,C^2_r) = 0,1 \end{array}\right\} r = \mathrm{a},\ \mathrm{e_u},\ \mathrm{e_l} \oplus \mathrm{b} \quad (25)$$

$$\mathbf{I}_{\mathrm{III}}(H^1_r,\emptyset,C^1_r,\emptyset) \ge \mathbf{I}_{\mathrm{I}}(H^1_r,\emptyset,C^1_r,\emptyset) \qquad r = \mathrm{a} \oplus \mathrm{e_u},\ \mathrm{e_l},\ \mathrm{b} \quad (26)$$

$$\mathbf{I}_{\mathrm{III}}(H^2_r,\emptyset,C^2_r,\emptyset) \ge \mathbf{I}_{\mathrm{I}}(H^2_r,\emptyset,C^2_r,\emptyset) \qquad r = \mathrm{a},\ \mathrm{e_u},\ \mathrm{e_l} \oplus \mathrm{b} \quad (27)$$

Model P4 first considers the set of constraints 7 and 11 that correspond to the regions of each plant in conditions of no integration. Then, constraints 22 and 23 account for the same regions when integration is performed. To avoid matches not required during integration, constraints 24 and 25 are included. Finally, constraints 26 and 27 require that matches between streams belonging to one of the plants working independently also are present in conditions of integration across plants.

3.11. Intersecting Heat-Exchanger Networks. The modifications in the objective function and the addition of constraints to models $P2_1$ and $P2_2$ were implemented to prevent exchangers idle in either one of the modes of operation (e.g., exchangers E2 and E4 in Figure 3) from exchanging heat when not required to do so. As previously discussed, the existence of exchangers that become idle in any of the working conditions constitutes a degree of flexibility in the operation of a heat-exchanger network. Switch of modes can be, in some circumstances, a way of putting the units that become idle out of operation for cleaning purposes. Yet, another possibility is the utilization of a single exchanger unit that works with different streams in the nonintegrated and integrated modes. This suggests the following definition: an intersecting multipurpose heat-exchanger network is one in which the heat exchangers matching hot and cold streams belonging to the plant under consideration are present in both stand-alone and across-plants integration, either to exchange heat between the same streams in both cases or to change them with the switch in the mode of operation. Heat exchangers used for any type of integration, direct or not, are not necessarily new heat exchangers.

After models $P3_1$ and $P3_2$ are solved for indirect integration and model P4 is solved for direct integration, situations such as case 2 and cases 4−7 of Table 2 are identified easily. Then, designing an intersecting multipurpose heat-exchanger network offers an advantage because the total number of heat-exchanger units can be reduced. For example, the simultaneous appearance of case 4 with one of the cases 5−7 (usually forming a loop) opens the possibility of implementing a series of bypasses to change streams from one mode of operation to the other and to make possible the use of a single heat-exchanger unit. In turn, in case 2, change of only one of the streams of the heat-exchanger unit is required.

4. Results

In this section, all of the concepts previously presented are applied to the design of multipurpose heat-exchanger networks for the three examples reviewed in the target energy savings section. These examples were selected from Rodera and Bagajewicz[4] in which hot and

Table 3. Sizes of the MILPs and CPU Times Required for the Solution of Examples 1−3

example	type of integration	con- straints	continuous variables	binary variables	CPU time (s)
1	indirect	259	301	54	0.371
	direct	266	310	55	0.631
2	indirect	604	664	120	0.761
	direct	551	631	119	0.641
3	indirect	803	872	146	1.052
	direct	762	847	145	0.691

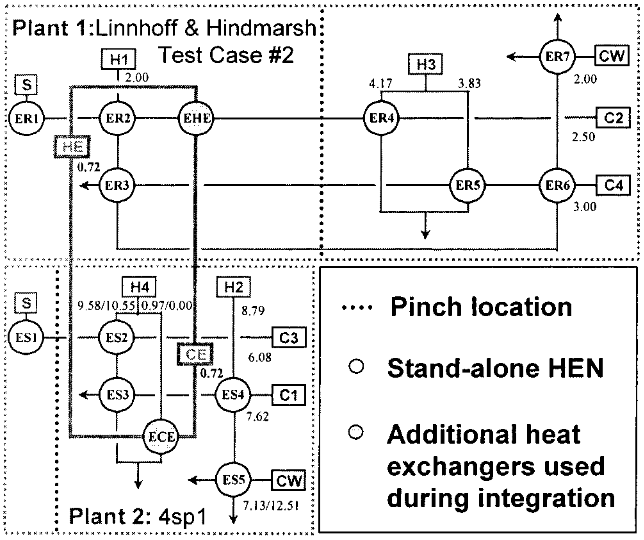

Figure 4. Indirect-integration heat-exchanger network for example 1.

cold stream data is available. The MILP models presented are programmed in GAMS and solved by using the CPLEX solver.[12] Sizes of the MILP formulations and the CPU time required to solve them on a Pentium PC for every example are given in Table 3.

4.1. Example 1. This example consists of test case 2 (L&H) from Linnhoff and Hindmarsh[7] (plant 1) and problem 4sp1 (plant 2). Applying pinch analysis resulted in a combined-plant pinch temperature located at the same level as the pinch temperature of plant 2 for both direct and indirect integration.[4] Therefore, three of the four heat-transfer regions depicted in Figure 2 are considered for the design (i.e., no partition of the region between pinch temperatures is required). As a result, the integration takes place in a single effective heat-transfer region, e_I, below the combined-plant pinch temperature and above the pinch temperature of plant 1.

4.1.1. Indirect Integration. The solution to model $P3_1$ results in a network containing eight heat-exchanger units for plant 1, including the additional heat-exchanger unit using the hot intermediate-fluid stream required only during indirect integration. Similarly, the solution to model $P3_2$ results in a network containing six heat-exchanger units for plant 2, including the heat-exchanger unit using the cold intermediate-fluid stream. Figure 4 shows the resulting design of the heat-exchanger network of the entire system for the case in which the minimum possible heat capacity flow rate for the intermediate-fluid stream is used (0.72 kW/°C). This corresponds to a targeting circuit solution covering all intervals between pinch temperatures.

Heat-exchanger unit specifications for the network of Figure 4 are presented in Table 4. Notice that the steam heater unit used during plant 1 stand-alone operation becomes idle during integration because the intermediate-fluid stream is capable of supplying the total amount of heating demand. This situation is predicted by the solution to model $P3_1$, which results in a network requiring seven heat-exchanger units for plant 1 when it is working during integration. The concept of intersecting heat-exchanger networks can be applied here by using a single heat-exchanger unit that works with different streams depending on the mode of operation.

4.1.2. Direct Integration. The heat-exchanger network design obtained after solving the direct integration model, P4, is shown in Figure 5. It consists of 13 heat-exchanger units with only one additional unit used during integration. In this case, instead of using an intermediate-fluid circuit, a match between cold stream C2 of plant 1 and hot stream H4 of plant 2 is required during integration conditions.

A branch of hot stream H4 is chosen to extend across plants to deliver the effective heat from plant 2 to plant 1. This results in a minimum heat capacity flow rate of 0.68 kW/°C that is lower than the minimum possible value for the case of indirect integration using an intermediate-fluid stream. The explanation for a higher value for the minimum heat capacity flow rate when the intermediate-fluid stream is used stems from the additional minimum temperature difference required to extract the heat from hot stream H4.

The disadvantages of having to pump at a higher flow rate for indirect integration (when the heat capacities of the process stream and intermediate-fluid stream are equal) and the additional heat-exchanger unit that is required are the price paid for using a closed circuit that may have process control and security advantages. However, a trade-off analysis of the pumping cost incurred in delivering the effective heat needs to take into account that when the heat capacity of the intermediate-fluid stream is higher than that of the process stream, savings in pumping costs can be expected to compensate for the cost of the additional heat-exchanger unit. Further analysis is not performed, because the problems used in this example are not related to real situations.

Table 5 shows the heat-exchanger unit specifications for the direct-integration network of Figure 5. As in indirect integration, the steam heater unit used during plant 1 stand-alone operation becomes idle during integration. The solution to model P4 predicts this result by requiring a network containing only 12 heat-exchanger units for the entire network when it is integrated.

4.2. Example 2. In this example, a problem from Trivedi[8] is plant 1 and example 1 from Ciric and Floudas[9] is plant 2. As in example 1, the combined-plant pinch temperature is located at the same level as the pinch temperature of plant 2 for both direct and indirect integration.[4] The effective transfer takes place in a single effective heat-transfer region, e_I, below the combined-plant pinch temperature and above the pinch temperature of plant 1. The presence of a gap in the temperature scale for the heat cascade of plant 2 during indirect integration represents a reduction of this region when an intermediate-fluid circuit is used. Assisting heat transfer takes place in the region a above both pinch temperatures.

4.2.1. Indirect Integration. When model $P3_1$ is solved, a network containing 18 heat-exchanger units for plant 1, including three additional heat-exchanger

Table 4. Indirect-Integration Heat-Exchanger Network Specifications for Example 1

heat exchanger	heat load (kW)[a]	hot side temp (°C)[a]		cold side temp (°C)[a]	
ER1	0.0/107.5	NA/270	NA/125	NA/270	NA/82
ER2	30.0	150	125/82	135	113/70
ER3	90.0	135	100	90	70
ER4	125.0	90	70	60	20
ER5	115.0	90	70	60	31.7
ER6	40.0	90	31.7	80	25
ER7	20.0	80	40	60	20
ES1	127.7	270	260	270	239
ES2	747.8	249	239	170.9/178.1	116
ES3	315.7/423.2	170.9/178.1	160	138	118.6/104.5
ES4	446.3/338.8	160	118.6/104.5	109.2/121.5	60
ES5	142.6/250.1	109.2/121.5	40	93	20
EHE	107.5/0.0	239/NA	113/NA	90/NA	70/NA
ECE	107.5/0.0	249/NA	239/NA	138/NA	90/NA

[a] Integration/stand-alone operation. NA = nonapplicable.

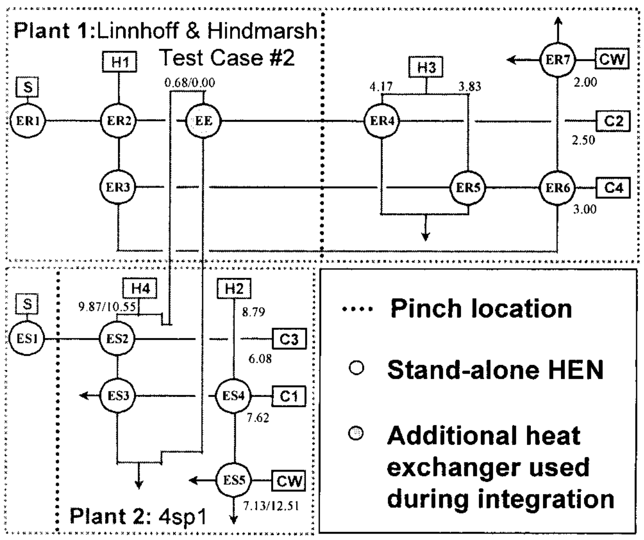

Figure 5. Direct-integration heat-exchanger network for example 1.

units used only during indirect integration, is obtained. These units are a unit matching hot stream H3 with cold stream C2, a unit transferring effective heat to plant 1 via a hot intermediate-fluid stream (effective intermediate-fluid circuit), and a unit extracting assisting heat from plant 1 via a cold intermediate-fluid stream (assisting intermediate-fluid circuit). Similarly, solving model $P3_2$ for plant 2 results in a network containing nine heat-exchangers units, including two additional heat-exchanger units. In the first heat exchanger, a cold intermediate-fluid stream is used to extract the effective heat from plant 2 (effective intermediate-fluid circuit). The second heat exchanger is used to transfer assisting heat to plant 2 via a hot intermediate-fluid stream (assisting intermediate-fluid circuit). Figure 6 shows the resulting heat-exchanger network for the entire system in which the previously obtained targeting values of flow rate and temperatures for the effective and assisting intermediate-fluid circuits are used.[4]

Table 6 shows the heat-exchanger unit specifications for the network of Figure 6. The case consists of a purely additive multipurpose heat-exchanger network, and the additional heat exchangers used during indirect integration become idle during stand-alone operation.

4.2.2. Direct Integration. Figure 7 shows the heat-exchanger network design obtained after solving the direct integration model, P4, for this assisted heat-integration example. The design consists of 25 heat-exchanger units with three additional units used during integration. Two of these additional heat-exchanger units transfer the total amount of effective heat and match hot stream H6 of plant 2 with cold streams C2 and C3 of plant 1. The third additional heat-exchanger unit transfers assisting heat and matches hot stream H4 of plant 1 with cold stream C4 of plant 2.

A comparison of the indirect-integration heat-exchanger network of Figure 6 with the direct-integration heat-exchanger network of Figure 7 follows. Two intermediate-fluid circuits are required in indirect integration, while direct integration requires three process streams to extend across plants. The summation of flow rates, however, is smaller for the direct-integration case. Moreover, energy savings, as determined by targeting, are 60% higher when this form of integration is used. Similar to example 1, the problems used in this example are not related to real situations so further analysis is not performed. Heat-exchanger unit specifications for the direct-integration network of Figure 7 are shown in Table 7.

4.3. Example 3. The last example consists of a crude unit processing 150 000 bbl/day and an FCC plant processing 40 000 bbl/day. The crude unit is plant 1, while the FCC unit is plant 2. Analysis of the combined-plant pinch temperature reveals that it is located at a temperature between the pinch temperatures of the plants for both direct and indirect integration.[4] All of the regions depicted in Figure 2 have to be considered for the design of a heat-exchanger network. For the combined-plant pinch temperature to exist during integration, the maximum amount of energy savings obtained by the targeting procedures must be used (Table 1). Therefore, in the case of indirect integration, the targeting solution containing two intermediate-fluid circuits is considered first.

4.3.1. Indirect Integration Using Two Intermediate-Fluid Circuits. The solution to model $P3_1$ gives a network containing 25 heat-exchanger units for plant 1, which includes three additional heat-exchanger units used only during indirect integration. One of these additional units is used to transfer heat from hot stream H9 to cold stream C3. The other units transfer effective heat to cold stream C2 of plant 1 by the use of two hot intermediate-fluid streams. These two hot streams correspond to the effective intermediate-fluid circuits. One of them is located above the combined-plant pinch temperature and the other below this temperature. In turn, solving model $P3_2$ for plant 2 results in a network containing 13 heat-exchanger units, including six ad-

Table 5. Direct-Integration Heat-Exchanger Network Specifications for Example 1

heat exchanger	heat load (kW)[a]	hot side temp (°C)[a]		cold side temp (°C)[a]	
ER1	0.0/107.5	NA/270	NA/125	NA/270	NA/82
ER2	30.0	150	125/82	135	113/70
ER3	90.0	135	100	90	70
ER4	125.0	90	70	60	20
ER5	115.0	90	70	60	31.7
ER6	40.0	90	31.7	80	25
ER7	20.0	80	40	60	20
ES1	127.7	270	260	270	239
ES2	747.8	249	239	173.2/178.1	116
ES3	315.7/423.2	173.2/178.1	160	141.2	118.6/104.5
ES4	446.3/338.8	160	118.6/104.5	109.2/121.5	60
ES5	142.6/250.1	109.2/121.5	40	93	20
EE	107.5/0.0	249/NA	113/NA	90/NA	70/NA

[a] Integration/stand-alone operation. NA = nonapplicable.

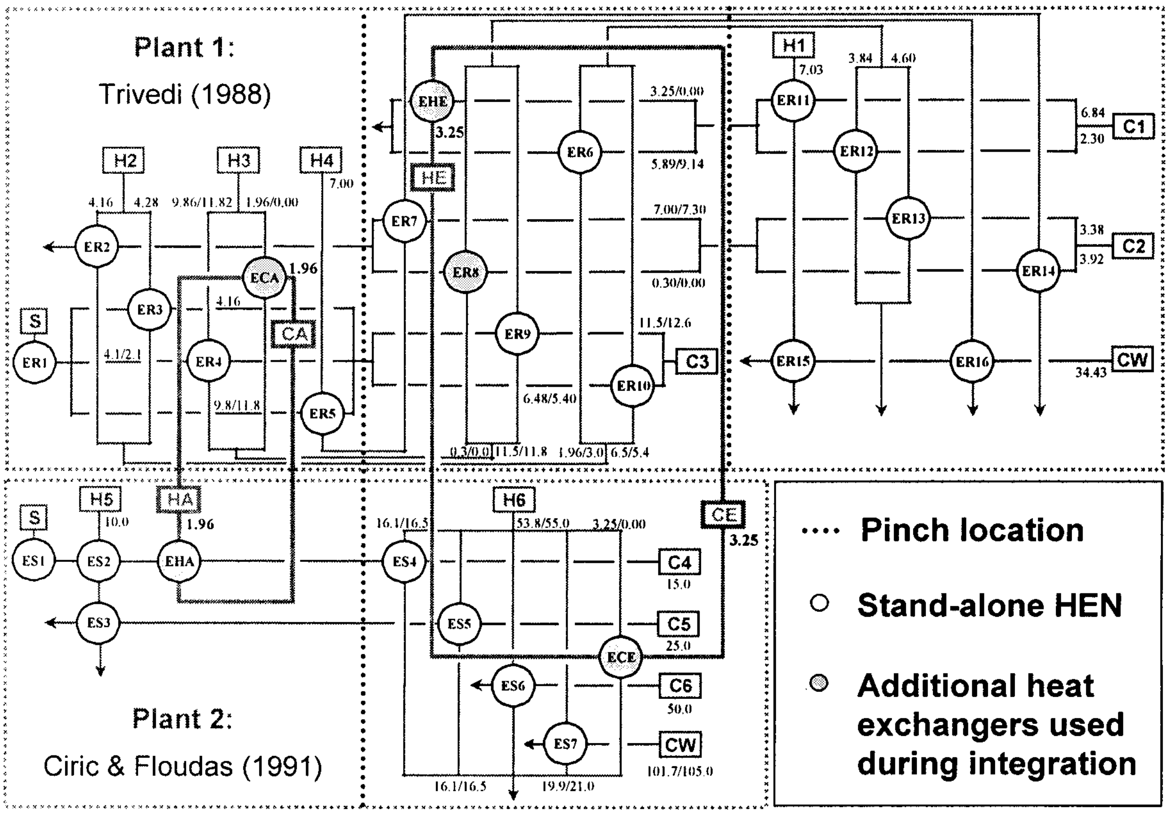

Figure 6. Indirect-integration heat-exchanger network for example 2.

ditional heat-exchanger units. Two cold intermediate-fluid streams, one using five units and the other using one unit, extract the effective heat from several hot streams of plant 2. They correspond to the two effective intermediate-fluid circuits expanding across plants at both sides of the combined-plant pinch temperature. Figure 8 shows the resulting heat-exchanger network for the entire system. The heat capacity flow rates for each of the intermediate-fluid circuits are the minimum possible to reduce pumping costs.

Heat-exchanger unit specifications for the network of Figure 8 are shown in Table 8. The presence of idle heat exchangers during conditions of stand-alone operation is obvious from the additive nature of the model employed. However, notice that the unit used to transfer heat from hot stream H5 to cold stream C2 during stand-alone operation of plant 1 becomes idle during indirect integration. A heat loop involving heat exchangers ER2 to ER5 is present, and the heat loads are accommodated in the loop to leave unit ER3 idle during stand-alone operation and unit ER4 idle during integration. The existence of the loop, as it was previously discussed, can be a way of reducing the overall cost of the network by using units ER3 and ER4 to fulfill part of the demand for heat from the corresponding cold streams during the modes of operation in which the heat exchangers become idle. Breaking the loop by applying the concept of intersecting multipurpose heat-exchanger networks results in one less heat-exchanger unit. Another heat exchanger that becomes idle during integration conditions is unit ES7, representing the use of a cooler used to bring stream H14 to its target temperature. The existence of idle exchangers present during integration conditions is identified by the solution to models $P3_1$ and $P3_2$, which predict a network with 24 and 12 heat-exchanger units, respectively.

4.3.2. Direct Integration. After the direct-integration model, P4, is solved, the heat-exchanger network design obtained is shown in Figure 9. The design consists of 36 heat-exchanger units with seven ad-

Table 6. Indirect-Integration Heat-Exchanger Network Specifications for Example 2

heat exchanger	heat load (kW)[a]	hot side temp (°C)[a]		cold side temp (°C)[a]	
ER1	353.3/404.8	300	250	300	230.4/227.5
ER2	124.0	249	217	220	200
ER3	120.7	249	229	220	200
ER4	69.0/35.2	227	217	220/224	200
ER5	357.0/339.2	271	236.5/228.2	220/222.5	200
ER6	117.6/182.9	220	160	160	140
ER7	420.0/437.8	220/222.5	200	160	140
ER8	17.8/0.0	220/NA	200/NA	160/NA	140/NA
ER9	691.2/756.5	220/224	200	160	140
ER10	388.8/323.5	220	200	160	140
ER11	301.1	160	140	117.2	96
ER12	101.3	160	140	138	96
ER13	84.4	160	140	138	115
ER14	98.0	160	140	146	115
ER15	50.5	117.2	90	110	70
ER16	638.1	160	88.5	106	70
ES1	586.3/600.0	300	270	300	230.9/230
ES2	750.0	300	230.9/230	225	180.9/180
ES3	250.0	225	190	200	180
ES4	1650.0	200	180	97.8/100	70
ES5	2750.0	200	180	97.8/100	70
ES6	550.0	200	180	97.8/100	70
ES7	2034.7/2100.0	200	180	97.8/100	70
ECA	13.7/0.0	227/NA	207/NA	220/NA	200/NA
EHA	13.7/0.0	207/NA	180.9/NA	200/NA	180/NA
EHE	65.3/0.0	239/NA	113/NA	90/NA	70/NA
ECE	65.3/0.0	249/NA	239/NA	138/NA	90/NA

[a] Integration/stand-alone operation. NA = nonapplicable.

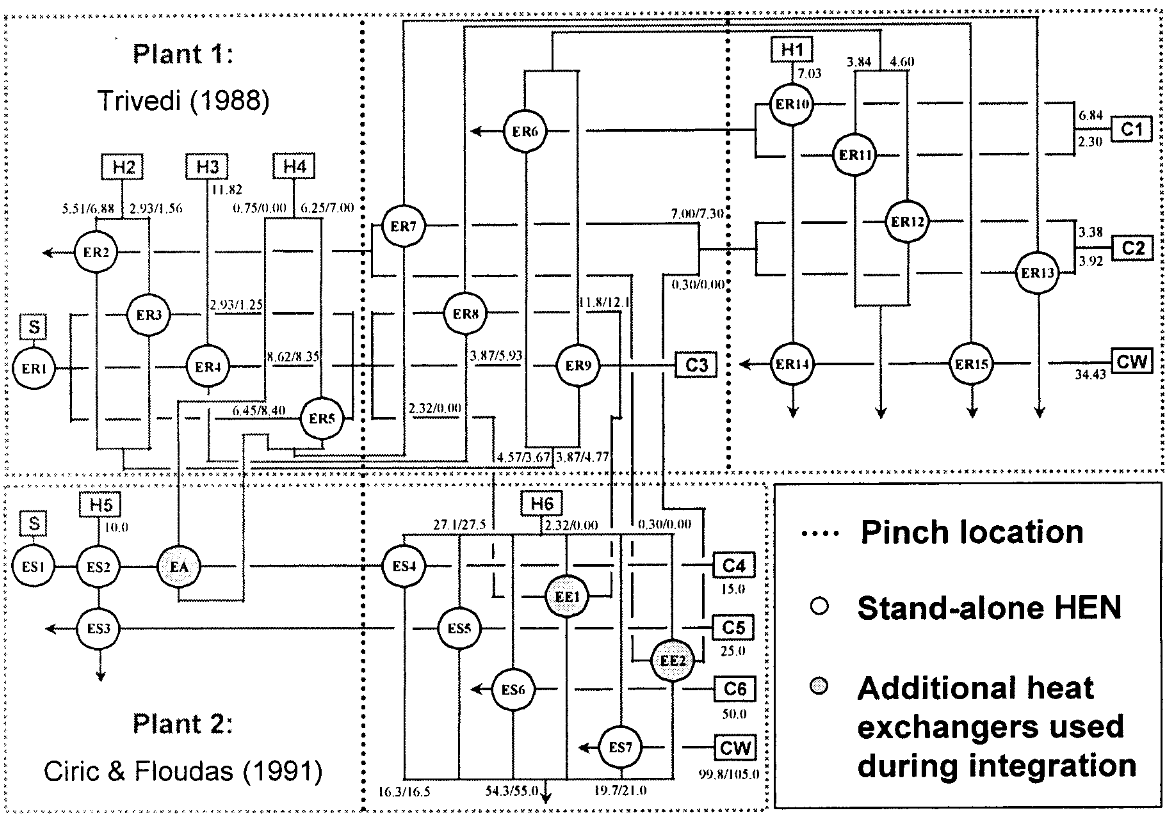

Figure 7. Direct-integration heat-exchanger network for example 2.

ditional units used only during integration. One of these additional heat-exchanger units (as was the case for indirect integration) transfers heat from hot stream H9 to cold stream C3 in plant 1. The other six additional heat-exchanger units transfer heat from plant 2 to plant 1. Five units are used above the combined-plant pinch temperature to transfer heat from several hot streams of plant 2 to cold stream C2 of plant 1. Below the combined-plant pinch temperature, transfer of heat from hot stream H15 of plant 2 to cold stream C2 of plant 1 takes place in the sixth unit. Exactly the same minimum heat capacity flow rate value used for each of the two intermediate-fluid circuits can be obtained for the each of the two splits of cold stream C2 that extend across plants. Therefore, if equal heat capacities for the intermediate-fluid stream and cold stream C2

Table 7. Direct-Integration Heat-Exchanger Network Specifications for Example 2

heat exchanger	heat load (kW)[a]	hot side temp (°C)[a]		cold side temp (°C)[a]	
ER1	353.3/404.8	300	250	300	230.4/227.5
ER2	270.0	249	217	200/209.8	180
ER3	143.6/61.2	249	229	200/209.8	180
ER4	319.0/308.8	227	217	200/200.9	180
ER5	444.1/485.2	271	248.9/237.8	200/201.7	180
ER6	182.9	200/209.8	160	160	140
ER7	280.0/291.8	200/201.7	180	160	140
ER8	472.6/482.8	200/200.9	180	160	140
ER9	154.7/237.2	200/209.8	180	160	140
ER10	301.1	160	140	117.2	96
ER11	101.3	160	140	138	96
ER12	84.4	160	140	138	115
ER13	98.0	160	140	146	115
ER14	50.5	117.2	90	110	70
ER15	638.1	160	88.5	106	70
ES1	547.1/600.0	300	270	300	233.5/230
ES2	750.0	300	233.5/230	225	183.5/180
ES3	250.0	225	190	200	180
ES4	1650.0	200	180	98.6/100	70
ES5	2750.0	200	180	98.6/100	70
ES6	550.0	200	180	98.6/100	70
ES7	1995.5/2100.0	200	180	98.6/100	70
EA	52.9/0.0	271/NA	233.5/NA	200/NA	180/NA
EE1	92.6/0.0	200/NA	180/NA	160/NA	140/NA
EE2	11.8/0.0	200/NA	180/NA	160/NA	140/NA

[a] Integration/stand-alone operation. NA = nonapplicable.

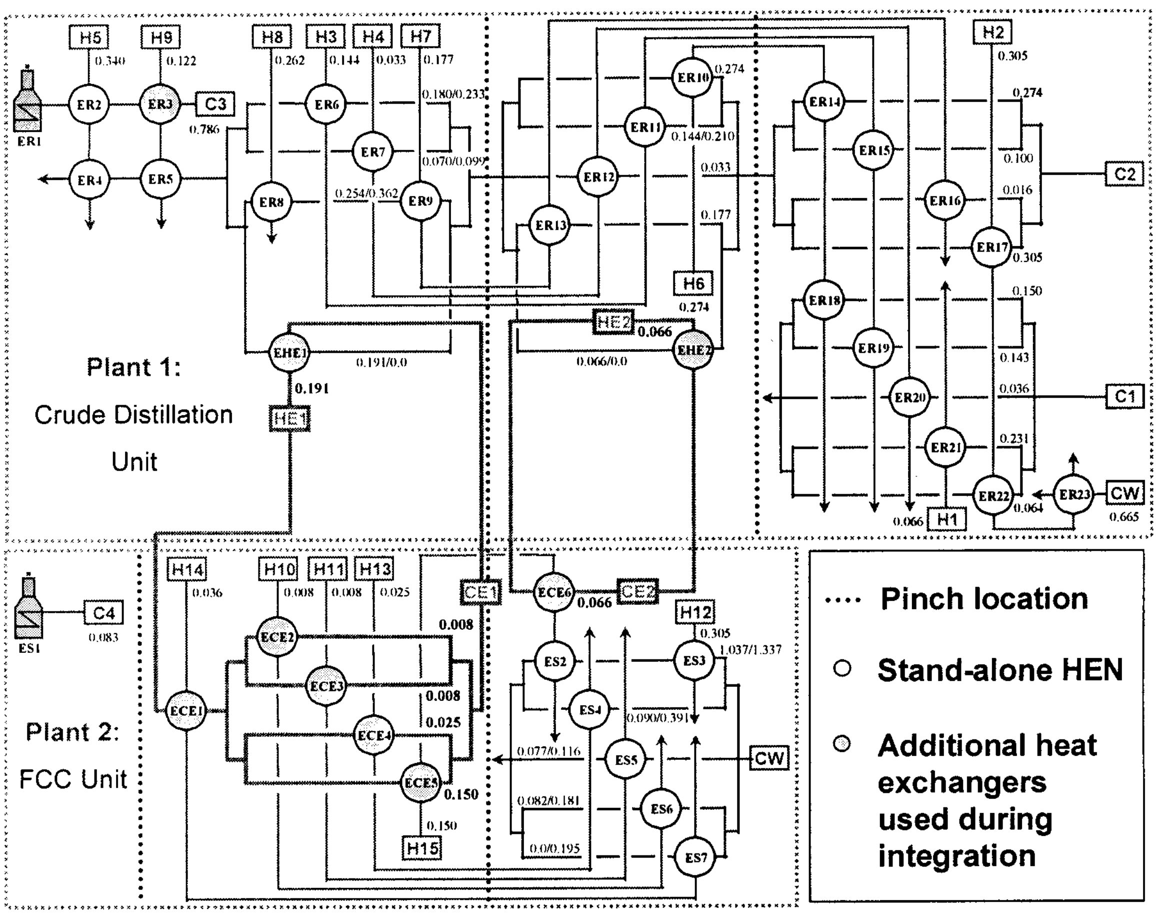

Figure 8. Two intermediate-fluid circuits heat-exchanger network for example 3.

are assumed, a lower total cost can be expected for the multipurpose heat-exchanger network that performs direct integration. The reasons for a higher cost when indirect integration is used are the two additional units required and the resulting energy savings that are 8% lower than direct integration.

Table 9 shows the heat-exchanger unit specifications for the direct integration network of Figure 9. The loop previously described for indirect integration also exists for direct integration, and the previously presented analysis is valid for direct integration. Moreover, in addition to heat exchanger ER4, heat exchanger ES7

Table 8. Two Intermediate-Fluid Circuits Heat-Exchanger Network Specifications for Example 3

heat exchanger	heat load (MW)[a]	hot side temp (°C)[a]		cold side temp (°C)[a]	
ER1	55.03/69.04	427.2	352.9	427.2	282.9/265
ER2	26.86/20.19	347.3	282.9/265	268.3/287.9	248.7/239.3
ER3	7.34/0.0	336.3/NA	248.7/NA	276.1/NA	239.3/NA
ER4	0.0/6.67	NA/287.9	NA/239.3	NA/268.3	NA/229.7
ER5	4.42/11.78	276.1/336.3	239.3/229.7	239.8	232.9/212.7
ER6	14.12/12.82	261.4	236.3/212.7	163.3/172.3	157.7
ER7	5.46	326.7	236.3/212.7	163.3	157.7
ER8	14.42	261.4	236.3/212.7	206.3	157.7
ER9	5.53	194.5	179.5/173	163.3	157.7
ER10	5.43	163.3	157.7	143.5	137.9
ER11	2.85/4.15	163.3/172.3	157.7	143.5	137.9
ER12	0.66	163.3	157.7	143.5	137.9
ER13	3.51	163.3	157.7	143.5	137.9
ER14	2.91	143.5	137.9	132.9	127.3
ER15	1.06	143.5	137.9	136.1	127.3
ER16	0.16	143.5	137.9	142.6	127.3
ER17	3.24	143.5	137.9	132.9	127.3
ER18	14.63	132.9	127.3	79.6	30
ER19	14.15	136.1	129.3	37.8	30
ER20	3.53	143.5	129.3	37.8	30
ER21	5.86	127.3	121.7	37.8	30
ER22	22.45	132.9	127.3	59.4	30
ER23	9.98	59.4	30	26.7	15
ES1	5.080	538.3	532.2	538.3	471.1
ES2	7.97/12.46	168.9/243.9	30	107.2	22.3/20.7
ES3	7.59	147.2	22.3/20.7	48.9	15
ES4	1.35/5.86	168.9/348.2	30	115.5	15
ES5	1.15/1.74	168.9/190.1	30	21.1	15
ES6	1.23/2.72	168.9/348.2	30	21.1	15
ES7	0.0/2.93	NA/313.2	NA/30	NA/232.2	NA/15
EHE1	12.71/0.0	229.6/NA	224/NA	163.3/NA	157.7/NA
EHE2	1.30/0.0	163.3/NA	157.7/NA	143.5/NA	137.9/NA
ECE1	2.93/0.0	313.2/NA	229.6/NA	232.2/NA	214.3/NA
ECE2	1.50/0.0	348.2/NA	342.6/NA	168.9/NA	163.3/NA
ECE3	0.60/0.0	243.9/NA	238.3/NA	168.9/NA	163.3/NA
ECE4	4.52/0.0	348.2/NA	342.6/NA	168.9/NA	163.3/NA
ECE5	3.19/0.0	190.1/NA	184.5/NA	168.9/NA	163.3/NA
ECE6	1.30/0.0	168.9/NA	163.3/NA	160.2/NA	143.5/NA

[a] Integration/stand-alone operation. NA = nonapplicable.

becomes idle during direct integration, as was the case during indirect integration.

The location of the combined-plant pinch temperature between pinch temperatures in both types of integration has the disadvantage of decomposing the multipurpose heat-exchanger network design of plant 1 above its pinch temperature. Two heat-exchanger units must be used for the same predicted match if the match is present at both sides of the combined-plant pinch temperature. This is the case of the matches between hot streams H3, H4, and H7 and cold stream C2 in plant 1. Thus, three fewer heat-exchanger units can be used if a certain amount of heat is allowed to pass through the combined-plant pinch temperature during integration conditions. Lower energy savings are obtained; however, the decrease in the number of units drastically reduces capital costs.

4.3.3. Indirect Integration Using a Single Intermediate-Fluid Circuit. The starting point for indirect integration is to consider the targeting solution that makes use of a single intermediate-fluid circuit (Table 1). The resulting heat-exchanger network design, without considering combined-plant pinch temperature partition is shown in Figure 10. It consists of 21 units, with only two additional units used during integration, one to transfer heat from hot stream H9 to cold stream C3 and the other to transfer effective heat from the intermediate-fluid stream to cold stream C2. To reduce pumping costs, the heat capacity flow rate for the circuit is the minimum possible.

Table 10 shows the heat-exchanger unit specifications for the network of Figure 10. The same analysis performed for the case of two intermediate-fluid circuits (Table 9) is valid in this case. Additionally, notice that in the heat-exchanger network of plant 1, only the heat-exchanger units participating in the loop rearrange their heat loads to switch from indirect integration to stand-alone operation mode.

4.3.4. Partial Direct Integration. For the case of direct integration, a similar reduction of three heat-exchanger units as in indirect integration can be achieved if partial energy savings are considered. When a certain amount of heat is allowed to pass through the combined-plant pinch temperature, matches located at both sides can be joined. The split of stream C2 that collects the greater amount of heat from plant 2 (similar to the single intermediate-fluid circuit solution) is therefore considered. Targeting energy savings are 13.8 MW, 10% higher than the targeting energy savings for a single intermediate-fluid circuit solution (Table 1). The resulting network, consisting of 33 heat-exchanger units, is shown in Figure 11, and the corresponding heat-exchanger unit specifications are shown in Table 11.

4.3.5. Use of Steam as Intermediate Fluid. In this section, we perform a comparison of indirect integration using intermediate-fluid circuits with indirect integration using steam. The graphic method using grand composite curves is employed to represent the maximum possible energy savings for indirect integration[4] and to

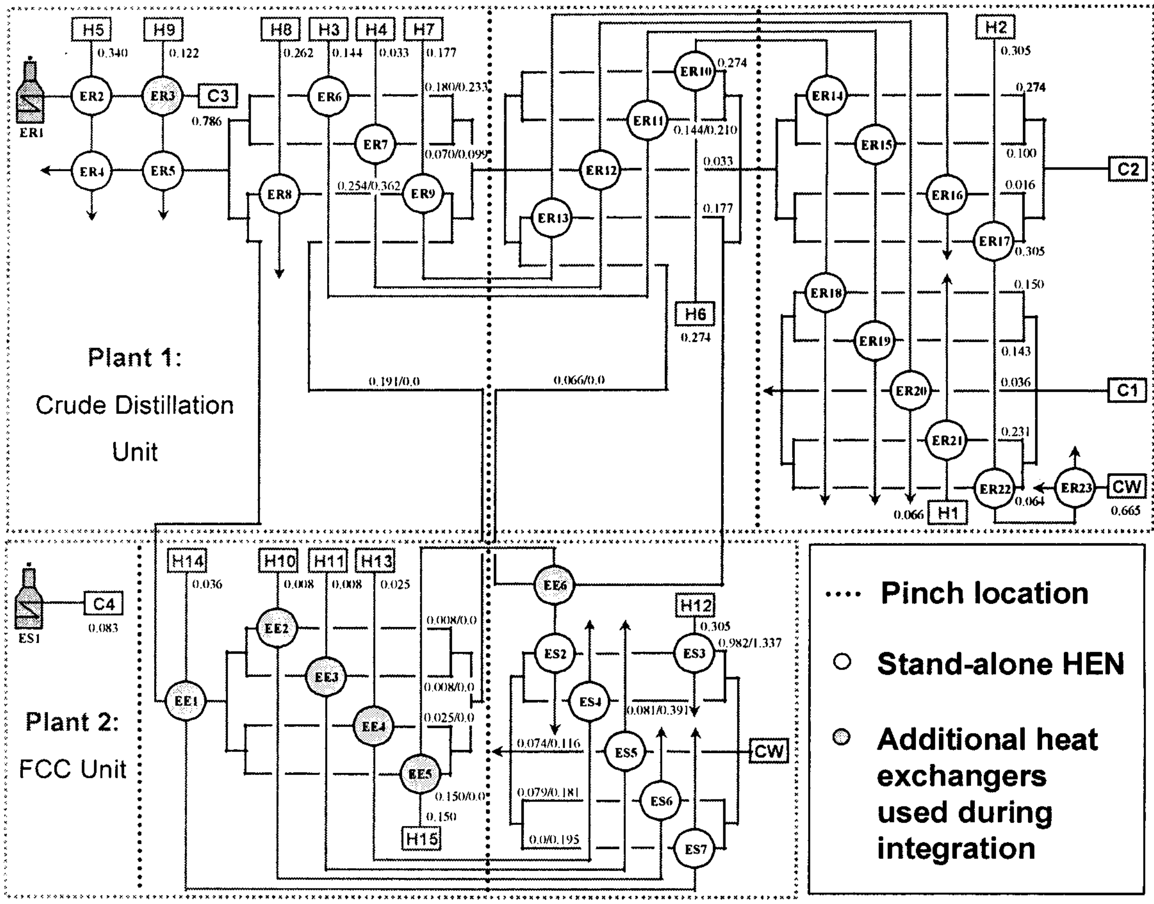

Figure 9. Direct-integration heat-exchanger network for example 3.

establish the possible levels at which steam can be generated and used. Figure 12 shows the composites for the region between pinch temperatures in which the effective heat integration is conducted.

Three standard steam levels are selected, and their specifications and heat transfer are shown in Table 12. The heat transfer values correspond to the maximum possible generation by plant 2 that can be limited by the amount of steam to be used by plant 1. In the case of generation of high- and medium-pressure steams between pinch temperatures, the limitation arises in plant 2 (level of steam touches plant 2 composite in Figure 12). The generation of low-pressure steam is limited by the possibility of this low-pressure steam level to be used by plant 1 above its pinch temperature. Only a small amount can be used for integration, which for practical purposes can be disregarded.

Therefore, the use of two exchangers for each of the steam levels considered (HP and MP) is necessary to generate in plant 2 and consume in plant 1 7.68 MW. This amount of energy savings is 45% lower than the maximum possible energy savings that are attained with two intermediate-fluid circuits and 40% lower than the energy savings attained by using a single intermediate-fluid circuit. Notice that only medium-pressure steam can be used to generate and consume the total amount of steam used for indirect integration. A tradeoff between the capital cost reduction by the use of only two heat exchangers in the latter case and the reduction in the minimum temperature difference when the steam is consumed is therefore required to decide on the best option.

5. Economical Analysis

As follows from the results of Example 3, the heat capacity flow rate for the split of cold stream C2 that extends across to plant 2 is equal to the minimum heat capacity flow rate for the intermediate-fluid circuit. Therefore, a priori comparison of the two networks favors direct integration over indirect integration. Besides the 10% higher energy savings, direct integration requires one less heat-exchanger unit. Pumping costs only can be higher if the intermediate fluid has a greater heat capacity than the crude stream. Usual intermediate fluids, such as dowtherms, perform with similar heat capacity to that of the crude for the range of temperatures considered in Example 3.

The real advantages of having a circuit that uses intermediate fluids are from the point of view of control and security. Moreover, the clean performance of intermediate fluids produces savings in the maintenance costs of the heat exchangers used for the integration. The simplified analysis that follows offers a comparison of the differences in magnitude of the total cost of the single-circuit indirect-integration and the partial direct-integration heat-exchanger networks studied in Example 3.

5.1. Installed Cost. The installed cost of the individual heat-exchanger units shown in Table 13 is computed by using the following simplified formula:[13]

$$\text{Installed Cost (\$)} = \frac{\text{M\&S}}{280} 21.6(A^{0.65})(2.29 + F_c) \quad (28)$$

where M&S is the Marshall and Swift cost index value

Table 9. Direct-Integration Heat-Exchanger Network Specifications for Example 3

heat exchanger	heat load (MW)[a]	hot side temp (°C)[a]		cold side temp (°C)[a]	
ER1	53.96/69.04	427.2	352.9	427.2	284.2/265
ER2	26.86/20.19	347.3	284.2/265	268.3/287.9	250/239.3
ER3	8.41/0.0	336.3/NA	250/NA	267.4/NA	239.3/NA
ER4	0.0/6.67	NA/287.9	NA/239.3	NA/268.3	NA/229.7
ER5	3.37/11.78	267.4/336.3	239.3/229.7	239.8	234.2/212.7
ER6	14.12/12.82	261.4	236.3/212.7	163.3/172.3	157.7
ER7	5.46	326.7	236.3/212.7	163.3	157.7
ER8	14.42	261.4	236.3/212.7	206.3	157.7
ER9	5.53	194.5	179.5/173	163.3	157.7
ER10	5.43	163.3	157.7	143.5	137.9
ER11	2.85/4.15	163.3/172.3	157.7	143.5	137.9
ER12	0.66	163.3	157.7	143.5	137.9
ER13	3.51	163.3	157.7	143.5	137.9
ER14	2.91	143.5	137.9	132.9	127.3
ER15	1.06	143.5	137.9	136.1	127.3
ER16	0.16	143.5	137.9	142.6	127.3
ER17	3.24	143.5	137.9	132.9	127.3
ER18	14.63	132.9	127.3	79.6	30
ER19	14.15	136.1	129.3	37.8	30
ER20	3.53	143.5	129.3	37.8	30
ER21	5.86	127.3	121.7	37.8	30
ER22	22.45	132.9	127.3	59.4	30
ER23	9.98	59.4	30	26.7	15
ES1	5.080	538.3	532.2	538.3	471.1
ES2	7.13/12.46	163.3/243.9	30	107.2	22.7/20.7
ES3	7.59	147.2	22.7/20.7	48.9	15
ES4	1.21/5.86	163.3/348.2	30	115.5	15
ES5	1.11/1.74	163.3/190.1	30	21.1	15
ES6	1.18/2.72	163.3/348.2	30	21.1	15
ES7	0.0/2.93	NA/313.2	NA/30	NA/232.2	NA/15
EE1	2.93/0.0	313.2/NA	229.6/NA	232.2/NA	214.3/NA
EE2	1.53/0.0	348.2/NA	342.6/NA	163.3/NA	157.7/NA
EE3	0.63/0.0	243.9/NA	238.3/NA	163.3/NA	157.7/NA
EE4	4.66/0.0	348.2/NA	342.6/NA	163.3/NA	157.7/NA
EE5	4.03/0.0	190.1/NA	184.5/NA	163.3/NA	157.7/NA
EE6	1.30/0.0	163.3/NA	157.7/NA	154.7/NA	137.9/NA

[a] Integration/stand-alone operation. NA = nonapplicable.

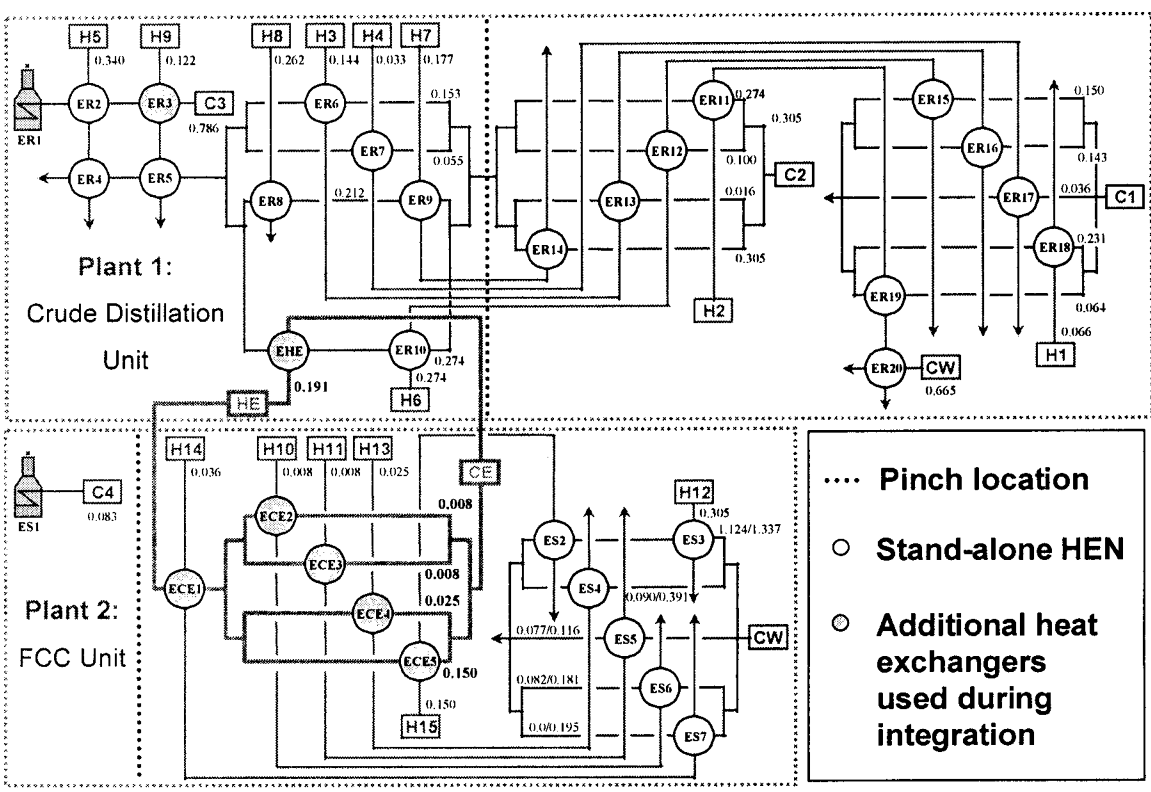

Figure 10. Single intermediate-fluid circuit heat-exchanger network for example 3.

Table 10. Single Intermediate-Fluid Circuit Heat-Exchanger Network Specifications for Example 3

heat exchanger	heat load (MW)[a]	hot side temp (°C)[a]		cold side temp (°C)[a]	
ER1	56.33/69.04	427.2	352.9	427.2	281.2/265
ER2	26.86/20.19	347.3	281.2/265	268.3/287.9	247/239.3
ER3	6.07/0.0	336.3/NA	247/NA	286.5/NA	239.3/NA
ER4	0.0/6.67	NA/287.9	NA/239.3	NA/268.3	NA/229.7
ER5	5.72/11.78	286.5/336.3	239.3/229.7	239.8	231.1/212.7
ER6	16.97	261.4	248.6	143.5	137.9
ER7	6.12	326.7	248.6	143.5	137.9
ER8	14.42	261.4	248.6	206.3	180.6
ER9	9.03	194.5	180.6	143.5	137.9
ER10	5.43	163.3	157.7	143.5	137.9
ER11	2.91	143.5	137.9	132.9	127.3
ER12	1.06	143.5	137.9	136.1	127.3
ER13	0.16	143.5	137.9	142.6	127.3
ER14	3.24	143.5	137.9	132.9	127.3
ER15	14.63	132.9	127.3	79.6	30
ER16	14.15	136.1	129.3	37.8	30
ER17	3.53	143.5	129.3	37.8	30
ER18	5.86	127.3	121.7	37.8	30
ER19	22.45	132.9	127.3	59.4	30
ER20	9.98	59.4	30	26.7	15
ES1	5.080	538.3	532.2	538.3	471.1
ES2	9.27/12.46	168.9/243.9	30	107.2	21.8/20.7
ES3	7.59	147.2	21.8/20.7	48.9	15
ES4	1.35/5.86	168.9/348.2	30	115.5	15
ES5	1.15/1.74	168.9/190.1	30	21.1	15
ES6	1.23/2.72	168.9/348.2	30	21.1	15
ES7	0.0/2.93	NA/313.2	NA/30	NA/232.2	NA/15
EHE1	12.71/0.0	229.6/NA	224/NA	163.3/NA	157.7/NA
ECE1	2.93/0.0	313.2/NA	229.6/NA	232.2/NA	214.3/NA
ECE2	1.50/0.0	348.2/NA	342.6/NA	168.9/NA	163.3/NA
ECE3	0.60/0.0	243.9/NA	238.3/NA	168.9/NA	163.3/NA
ECE4	4.52/0.0	348.2/NA	342.6/NA	168.9/NA	163.3/NA
ECE5	3.19/0.0	190.1/NA	184.5/NA	168.9/NA	163.3/NA

[a] Integration/stand-alone operation. NA = nonapplicable.

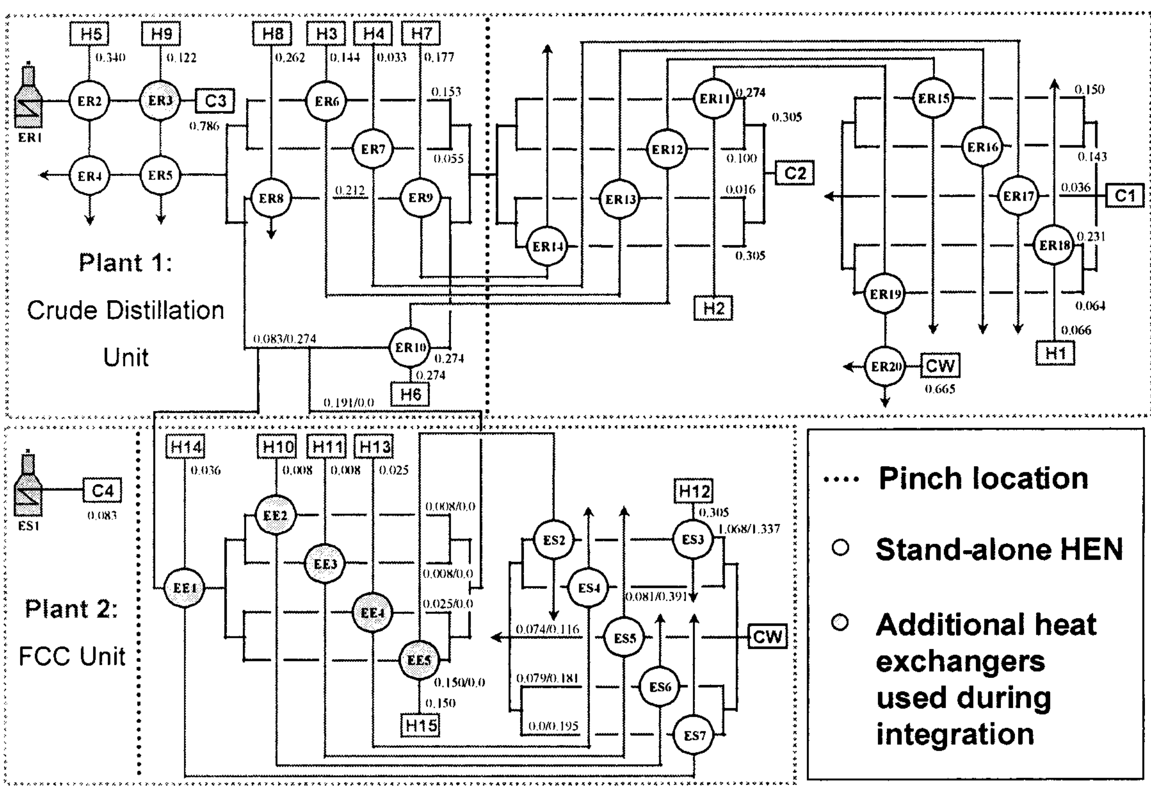

Figure 11. Partial-direct-integration heat-exchanger network for example 3.

for chemical and petrochemical plants (a value of 1130 is considered) and F_c is a correction factor. The largest heat-exchange areas are considered when the installed costs for the heat exchangers in which the heat load changes from integration to stand-alone mode of operation are computed. In the case of the furnaces, the following formula is used:[13]

$$\text{Installed Cost (\$)} = \frac{\text{M\&S}}{280} 1945(Q^{0.85})(1.27 + F_c) \quad (29)$$

Table 11. Partial-Direct-Integration Heat-Exchanger Network Specifications for Example 3

heat exchanger	heat load (MW)[a]	hot side temp (°C)[a]		cold side temp (°C)[a]	
ER1	55.26/69.04	427.2	352.9	427.2	282.6/265
ER2	26.86/20.19	347.3	282.6/265	268.3/287.9	248.4/239.3
ER3	7.15/0.0	336.3/NA	248.4/NA	277.7/NA	239.3/NA
ER4	0.0/6.67	NA/287.9	NA/239.3	NA/268.3	NA/229.7
ER5	4.62/11.78	277.7/336.3	239.3/229.7	239.8	232.6/212.7
ER6	16.97	261.4	248.6	143.5	137.9
ER7	6.12	326.7	248.6	143.5	137.9
ER8	14.42	261.4	248.6	206.3	180.6
ER9	9.03	194.5	180.6	143.5	137.9
ER10	5.43	163.3	157.7	143.5	137.9
ER11	2.91	143.5	137.9	132.9	127.3
ER12	1.06	143.5	137.9	136.1	127.3
ER13	0.16	143.5	137.9	142.6	127.3
ER14	3.24	143.5	137.9	132.9	127.3
ER15	14.63	132.9	127.3	79.6	30
ER16	14.15	136.1	129.3	37.8	30
ER17	3.53	143.5	129.3	37.8	30
ER18	5.86	127.3	121.7	37.8	30
ER19	22.45	132.9	127.3	59.4	30
ER20	9.98	59.4	30	26.7	15
ES1	5.080	538.3	532.2	538.3	471.1
ES2	8.43/12.46	163.3/243.9	30	107.2	22.1/20.7
ES3	7.59	147.2	22.1/20.7	48.9	15
ES4	1.21/5.86	163.3/348.2	30	115.5	15
ES5	1.11/1.74	163.3/190.1	30	21.1	15
ES6	1.18/2.72	163.3/348.2	30	21.1	15
ES7	0.0/2.93	NA/313.2	NA/30	NA/232.2	NA/15
EE1	2.93/0.0	313.2/NA	229.6/NA	232.2/NA	214.3/NA
EE2	1.53/0.0	348.2/NA	342.6/NA	163.3/NA	157.7/NA
EE3	0.63/0.0	243.9/NA	238.3/NA	163.3/NA	157.7/NA
EE4	4.66/0.0	348.2/NA	342.6/NA	163.3/NA	157.7/NA
EE5	4.03/0.0	190.1/NA	184.5/NA	163.3/NA	157.7/NA

[a] Integration/stand-alone operation. NA = nonapplicable.

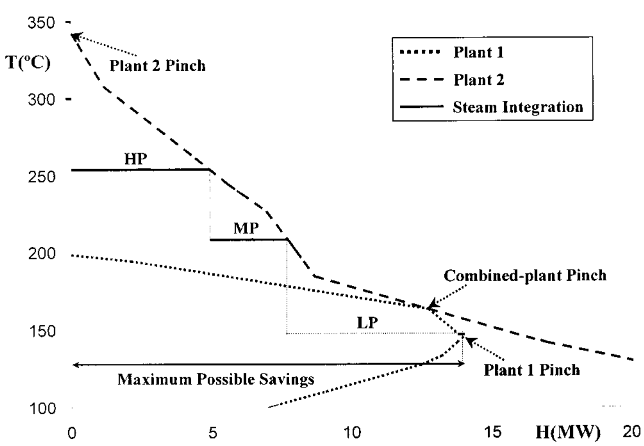

Figure 12. Indirect integration using steam for example 3.

Table 12. Installation Costs (Dollars) for Example 3

	single-circuit indirect integration	partial direct integration	difference (%)
total heat-exchanger network installation	21 700 000	20 450 000	5.8
total pipe installation	150 000	150 000	0.0
price intermediate fluid	405 000		100.0
total installation	22 255 000	20 600 000	7.4

The pipe-installation cost included in Table 13 is calculated for a closed-circuit pipe or for a split of the pipe corresponding to cold stream C2, both having 1000 m of length. Dowtherm A (with an average heat capacity of 2.06 kJ/(kg °C)) is considered as the intermediate fluid, and the cost of the fluid mass used in the closed circuit is included in Table 13. The crude is assumed to have a heat capacity of 2.6 kJ/(kg °C). The estimated optimum economic pipe diameter is 12 in. for both the

Table 13. Installation Costs (Dollars) for Example 3

	single-circuit indirect integration	partial direct integration	difference (%)
total heat-exchanger network installation	21 700 000	20 450 000	5.8
total pipe installation	150 000	150 000	0.0
price intermediate fluid	405 000		100.0
total installation	22 255 000	20 600 000	7.4

closed circuit and the split of cold stream C2. To estimate the cost of piping, the following formula is used:[14]

$$\text{Installed Cost of Piping (\$)} = \frac{\text{M\&S}}{904}[(1 + F)XD_i^{\,n}K_F]L \tag{30}$$

where D_i is the diameter, L is the length of the pipe, and F, X, and K_F are cost correction factors. To account for insulation costs, the obtained value is doubled using a rule of thumb. Finally, the total cost of installation for indirect and direct integration is shown in Table 13.

5.2. Operating Cost. To compute the total operating cost, furnace and pumping costs are calculated. The following formula is used for the estimation of the pumping costs:[14]

$$\text{Pumping Cost (\$)} = \frac{\text{M\&S}}{904}\left(\frac{(3.7 \times 10^{-5})q_f^{\,2.84}\rho^{0.84}\mu_c^{\,0.16}K(1 + J)H_y}{D_i^{\,4.84}E}\right) \tag{31}$$

where q_f is the volumetric flow rate, μ_c is the viscosity, and K, J, H_y, and E are cost correction factors. The results for the operating costs are shown in Table 14. Notice that the piping cost is 75% higher for the case of

Table 14. Operating Costs (Dollars) for Example 3

	single-circuit indirect integration	partial direct integration	difference (%)
furnace	4 130 000	4 058 000	1.7
pumping	18 200	10 400	75.0
total operating	4 148 200	4 068 400	1.9

Table 15. Total Annual Cost Comparison (Dollars) for Example 3

	single-circuit indirect integration	partial direct integration	difference (%)
total operating	4 148 200	4 068 400	1.9
heat-exchanger network amortization	2 225 500	2 060 000	7.4
total annual cost	6 373 700	6 128 400	3.8

the intermediate-fluid stream, but a comparison with the magnitude of the heating utility costs reduces the difference to 1.9%.

5.3. Total Annualized Cost. Considering a 10% amortization for the installation cost of Table 13, a total investment cost can be estimated. Table 15 shows the total annual cost after adding the operating and investment costs. A 3.8% difference favors direct integration, and this difference in cost is the price to pay for the use of an intermediate-fluid circuit for indirect integration.

6. Conclusions

The analysis of energy integration opportunities across plants has been somewhat dismissed in the past because of practical considerations. Nevertheless, some of these opportunities have been implemented without any theoretical counterpart. Rodera and Bagajewicz[4] discussed the targeting procedures for energy savings; this paper presents a methodology to design multipurpose heat-exchanger networks featuring the minimum number of heat-exchanger units. Indirect integration using intermediate-fluid circuits and direct integration using process streams were compared, and their advantages and disadvantages were discussed. A few new concepts, i.e., additive and intersecting heat-exchanger networks, have been proposed and discussed. In a final practical example that considers the integration of a crude distillation unit and an FCC unit, a comparison of the magnitude of the economics of the two types of integration is offered. The analysis of this example also reveals that the widely accepted statement that indirect integration using steam can achieve most of the energy savings in the total site is not valid when compared with an intermediate-fluid circuit.

Nomenclature

A = maximum heat exchanger area (m^2)
D_i = standard pipe diameter (in.)
E = efficiency of motor and pump expressed as a fraction
F = ratio of total costs for fitting and installation to purchase cost for new pipe
F_c = correction factor for heat exchanger installed cost
H_y = hours of operation per year
i = hot process stream
J = frictional loss due to fitting and bend, expressed as equivalent fractional loss in a straight pipe
j = cold process stream
K = cost of electrical energy (dollars/kWh)
K_f = annual fixed charges including maintenance, expressed as a fraction of initial cost of completely installed pipe
k = auxiliary hot/cold process stream
L_{ijr}^{T} = lower bound in the heat transfer between hot stream i and cold stream j within region r for type of integration T (kW)
p = chemical plant
q_f = fluid volumetric flow rate (m^3/s)
Q = absorbed duty for a process furnace (MW)
r = heat transfer region
t = temperature interval
U_{ijr}^{T} = upper bound in the heat transfer between hot stream i and cold stream j within region r for type of integration T (kW)
V_{ijt}^{T} = heat transfer from hot stream i to cold stream j in interval t for type of integration T (kW)
$\boldsymbol{W}_{it}^{H}$ = hot stream i heat duty in interval t
W_{jt}^{C} = cold stream j heat duty in interval t
X = purchase cost of new pipe per foot of 1-in. pipe length (dollars/m)
Y_{ijr}^{T} = heat transfer match between hot stream i and cold stream j within region r for type of integration T
Z_{ijr}^{T} = heat transfer match between hot stream i and cold stream j within region r for type of integration T
δ_{it}^{T} = cascaded heat of hot stream i from interval t for type of integration T (kW)
ρ = fluid density (kg/m^3)
μ_c = fluid viscosity (Pa s)

Stand-Alone Plants

N_r = set of temperature intervals corresponding to region r.
S_r = set of hot streams including heating utilities present in region r.
D_r = set of cold streams including cooling utilities present in region r.
S_t = set of hot streams including heating utilities present in temperature interval $\bar{t} \leq t$; $\bar{t}, t \in N_r$.
D_t = set of cold streams including cooling utilities present in temperature interval $t \in N_r$.

Integration across Plants

$\hat{S}_r$ = set of hot streams used for integration present in region r.
$\hat{D}_r$ = set of cold streams used for integration present in region r.
$\hat{S}_t$ = set of hot streams used for integration present in temperature interval $\bar{t} \leq t$; $\bar{t}, t \in N_r$.
$\hat{D}_t$ = set of cold streams used for integration present in temperature interval $t \in N_r$.

Single Plant

H_r^p = hot streams and heating utility streams present in region r of plant p.
C_r^p = cold streams and cooling utility streams present in region r of plant p.
In these sets, the values p = 1,2 correspond to plant 1 and plant 2, respectively.

Intermediate-Fluid Circuits

H_a^F = hot intermediate-fluid streams above the pinch temperature of plant 2, which correspond to circuits used in assisted cases. These are hot streams in plant 2.
C_a^F = cold intermediate-fluid streams above the pinch temperature of plant 2, which correspond to circuits used in assisted cases. These are cold streams in plant 1.

$H^F_{e_u}$ = hot intermediate-fluid streams between pinch temperatures above the combined-plant pinch temperature. These are hot streams in plant 1.

$C^F_{e_u}$ = cold intermediate-fluid streams between pinch temperatures above the combined-plant pinch temperature. These are cold streams in plant 2.

$H^F_{e_l}$ = hot intermediate-fluid streams between pinch temperatures below the combined-plant pinch temperature. These are hot streams in plant 1.

$C^F_{e_l}$ = cold intermediate-fluid streams between pinch temperatures below the combined-plant pinch temperature. These are cold streams in plant 2.

H^F_b = hot intermediate-fluid streams below the pinch temperature of plant 1, which correspond to circuits used in assisted cases. These are hot streams in plant 1.

C^F_b = cold intermediate-fluid streams below the pinch temperature of plant 1, which correspond to circuits used in assisted cases. These are cold streams in plant 2.

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