Optimization Model for Structural Modifications in the Retrofit of Heat Exchanger Networks

by

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OPTIMIZATION MODEL FOR STRUCTURAL MODIFICATIONS IN THE RETRORT OF HEAT EXCHANGER NETWORKS

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Abstract

This paper presents a systematic procedure for performing the fewest structural modifications in the retrofit of existing heat exchanger networks. An MILP assignment- transshipment model is proposed which has as objective to minimize first, matches that require new units and then matches that require reassignment of existing units. The special structure of this problem implies that its computational effort is similar to the MILP transshipment model for grassroots networks. The application of the proposed model is illustrated with two example problems.

INTRODUCTION

In recent years, the retrofit of existing heat exchanger networks (HEN) has become more important than the design of new networks. Much of this has to do with the fact that few new plants are being built, and that the profit margins in many processes are low. Since operating costs can often be reduced by improved energy recovery, there is the incentive to retrofit HEN's in existing plants. However, most of the previous research work has been directed to developing methods for the design of grassroots HEN's (e.g. Cerda and Westerberg (1983), Linnhoff and Hindmarsh, (1983), Floudas et al., (1986)). Therefore, there is a need to develop systematic procedures for retrofit designs.

The necessity of considering the existing exchanger network constitutes the major difference between retrofit and grassroots designs. In general, one cannot simply use grassroots methods to produce the final retrofit network. Consider as an example the retrofit of an existing network as shown in Figure 5. The retrofit modification of the grassroots network obtained by the method of Floudas et al. (1986) led to the results shown in Figure 7. It is apparent that the transformation of the existing network to the grassroots network would involve numerous modifications. Figure 6 shows a much better retrofit design of the network which requires fewer modifications, and which in fact was obtained with the procedure suggested in this paper.

Only a few papers have been published on the retrofit design of HEN's. For instance, Tjoe and Linnhoff (1986) have suggested as a basic guideline to remove existing stream matches that cross the pinch point in order to reduce the utility consumption. Jones et al. (1986) from Simulation Sciences Inc. have suggested a step-wise approach that mostly relies on the use of simulation to verify whether a proposed network modification will be close to achieving the minimum utility cost target. The main limitation, however, in these two procedures is that they are largely trial and error methods which do not explicitly address the question of how to systematically determine the required structural and parametric modifications in the network.

In this paper, an MILP assignment- transshipment model will be presented to determine the fewest structural modifications in the retrofit design of an existing network, and where the objective is to achieve the minimum utility cost for a specified temperature approach. As will be shown, the proposed model can be used within a systematic strategy for determining structural changes in the retrofit design. The application of this model will be illustrated with two example problems, where it is shown that some of the common guidelines for retrofit can actually fail.

OUTLINE OF STRATEGY

The problem that is specifically addressed in this paper is as follows:

Given are the structure and areas of an existing network. Given are also the stream conditions (flows and temperatures), as well as the desired recovery of energy. The problem then consists in determining a network structure that achieves the following objectives:

(a) Maximum utilization of existing exchanger units.

(b) Assignment of existing units to new required matches with minimum piping changes.

(c) Minimum number of new stream matches that require the installation and purchase of new units.

The motivation for the above objectives is that they will lead to a network with the fewest number of structural modifications, or in other words, to a network that is as close as possible to the existing one from a structural standpoint. Also, the above objectives do not require detailed costing information which is usually difficult to determine in the preliminary stage of a retrofit project.

This problem can be considered to be within an iterative scheme where various energy recovery levels are assumed, and where the modification of areas is evaluated at each step. That is, the steps in this procedure would be:

(1) Specify a minimum temperature approach to determine the minimum utility cost.

(2) Predict the required structural modifications in the network.

(3) Perform the retrofit network design to determine the area requirements.

(4) Determine the cost of the retrofit network to decide whether a new temperature approach (i.e. level of energy recovery) is to be investigated.

It is shown in this paper that the problem in step (2) can be formulated as an MILP assignment-transshipment problem. This model involves transshipment equations for the potential stream matches and special assignment constraints that account for the allocation of existing equipment to new services. The objective function contains terms that reflect the three objectives (a), (b), (c) stated above. An interesting feature of this model is that it can be shown that 0-1 assignment variables can be treated as continuous variables due to the special structure of the constraints. Therefore, this model has the same number of 0-1 variables as for predicting matches in the MILP transshipment model for grassroots design, and therefore it can also be solved very efficiently.

It should be noted that the proposed MILP formulation will be restricted to existing networks having only one subnetwork (i.e. no pinch point). This is a reasonable assumption as these networks are generally the ones for which additional energy recovery is possible. Also, for the sake of simplicity in the presentation, it will be assumed that each hot stream of the existing network matches at most one time with each cold stream. This assumption could easily be relaxed in the suggested model.

BACKGROUND

The MILP proposed formulation for retrofit is similar in nature to and can be viewed as an extension of the MILP transshipment model developed by Papoulias and Grossmann (1983). This model is summarized below.

First, the following definitions are necessary:

i) The sets:

H_{sk} = {/I/ e hot streams and stream i is present in temperature interval *k* or higher at subnetwork *s)*

^{c}*sk* = OV ^ cold streams and streamy is present in temperature interval *k,* subnetwork*s]*

H_s = *{i* hot stream *i* supplying heat to subnetwork *s)*

C_s = {/I cold streamy withdrawing heat from subnetwork *s}*

ii) The variables:

NS - number of subnetworks

Q^h_{ik} - heat load of hot stream i entering temperature interval k

Q^c_{jk} - heat load flowing to cold stream j from temperature interval k

Q_{ijk} - heat exchanged between hot stream i and cold stream j in temperature interval k

$R_{i,k}$ - heat residual of hot stream $i \in H_s$ in temperature interval k

SN_s - subset of temperature intervals corresponding to subnetwork s

U_{ijs} - an upper limit on the amount of heat that can be exchanged between hot stream i and cold stream j in subnetwork s

y_{ijs} - integer variable to denote the existence of a match between hot stream i and cold stream j in subnetwork s

With these definitions the MILP transshipment model that determines the fewest number of stream matches in a grassroots network is given by:

$$\min \sum_{s=1}^{NS} \sum_{i \in H_s} \sum_{j \in C_s} y_{ijs}$$

$$\text{s.t.} \quad R_{i,k} - R_{i,k-1} + \sum_{j \in C_{sk}} Q_{ijk} = Q^h_{ik} \qquad i \in H_{sk}\ ,\ k \in SN_s\ ,\ s=1,\ 2,\ \ldots\ NS$$

$$\sum_{i \in H_{sk}} Q_{ijk} = Q^c_{jk} \qquad j \in C_{sk}\ ,\ k \in SN_s\ ,\ s=1,\ 2,\ \ldots\ NS$$

$$\sum_{k \in SN_s} Q_{ijk} - U_{ijs}\, y_{ijs} \le 0 \qquad i \in H_s\ ,\ j \in C_s\ ,\ s=1,\ 2,\ \ldots\ NS \tag{P0}$$

$$R_{i,k} \ge 0 \qquad i \in H_{sk}\ ,\ k \in SN_s\ ,\ s=1,\ 2,\ \ldots\ NS$$

$$Q_{ijk} \ge 0 \qquad i \in H_{sk}\ ,\ j \in C_{sk}\ ,\ k \in SN_s\ ,\ s=1,\ 2,\ \ldots\ NS$$

$$y_{ijs} = 0,\ 1 \qquad i \in H_s\ ,\ j \in C_s\ ,\ s=1,\ 2,\ \ldots\ NS$$

For a more detailed description of this model, see Papoulias and Grossmann (1983).

To extend this formulation to the retrofit case, a modified objective function and additional constraints are required to take into account the existing matches, and to penalize for any required changes. However, all the constraints in *(PO)* would be the same since the balances for the heat flows remain unchanged. The next section will deal first with the case when only one subnetwork is involved in the retrofit network. That is, the minimum utility cost target can be achieved by the use of either only one heating or one cooling utility. The case of multiple subnetworks where one or several pinch points are involved will be treated later in the paper.

MODEL FOR ONE SUBNETWORK

In this section it will be assumed that the retrofit design can be accomplished by the use of a single heating or cooling utility. Also, since it is assumed that in the existing network each hot stream exchanges heat at most once with each cold stream, matches or units in the existing network have a one-to-one correspondence with matches or units in the retrofit network that involve the same pair of streams.

To convert the grassroots transshipment model to the retrofit case, it is first necessary to list the order of desirability of the different matches. The most desirable case is to have an existing match remain a match for the retrofit network, since this would maximize the use of existing units while minimizing the need for repiping in the existing network. Next, it is more favorable if a new match can be accomplished by changing only one of the streams in an existing match. With this, an existing exchanger can be utilized by repiping only one stream. Finally, it is least desirable to have a new match that requires the purchase and installation of a new exchanger, as well as new piping.

To account for the level of desirability of each match in the objective function, weights will be assigned to the binary variables for the matches to reflect the above priority scheme. In addition, special constraints need to be added to the grassroots transshipment model to account for the assignment of modifiable existing exchangers to new matches.

In order to formulate mathematically the problem for determining the matches for a retrofit network that involves a single subnetwork, it is convenient first to partition the set of all possible matches

M = {(ij)\i hot process/utility stream, *j* cold process/utility stream}

into the following sets:

E = {(iJ)KiJ) corresponds to a match in the existing network}

(1)

= {0V)>0V) does not correspond to a match in the existing network}

As in problem *(PO),* the binary variables $y_{t,J}$ will denote the selection of a match for the pair of streams *(ij).* As discussed above, the existing matches *(ij)e E* should be selected whenever possible, and therefore, they should have the lowest weights in the objective function. Although zero weights could be assigned to these matches, for computational considerations a small value e (e.g. e=0.01) will be assigned to these variables 3^, *(ij)eE.*

In the next two levels of priority, the selection of new matches *(ij)sN* will be assigned weights of one, with an additional penalty for those matches that require new units. Hence, the objective function for the retrofit design problem will have the form:

"d* X e y··* + X y· * + X w M*- (2)
(ij)e E (ij)e N (ij)e N

where ^ = 1 represents a new unit for match 07) e W» and *w* is a constant with a large value (e.g. *W*=*\ 00). If $\i_{tj}$ = 0 for a given y_{ij}• = 1, 07) e *W,* this will represent a new match 07) that can be performed by changing one of the streams in an existing match not included in the retrofit network. In order to model this condition it is necessary to consider additional constraints that account for the assignment of existing matches to new matches. This can be accomplished as follows:

Firstly, for each match *(ij)e E,* the two following sets are defined:

N(i) = {set of cold streams *k* with which hot stream *l* can be matched for *(ijt) e N]*

N{J) = {set of hot streams *k* with which cold stream *j* can be matched for *(kj) e N]* (3)

In this way, the 0-1 variable *z^p* will denote the assignment of existing match 07) to a new match *(ijc),* *ke N(i),* which involves only a change in the cold stream. Similarly, the 0-1 variable z£° will denote the assignment of match *(ij)* to a new match *(kj), ke N(j),* which involves only a change in the hot stream. Since the existing match *(ij)* can at most be assigned to one new match, the following assignment constraint applies:

$$\sum_{k \in N(i)} W + \underset{k \in N(j)}{\mathrm{I}} \; z\,\mathrm{S}^{\circ} \leq 1 - y_{ij} \qquad (i,j) \in \mathrm{E} \tag{4}$$

Note that if the existing match *(ij)e E* is selected *($y_{tJ'}$* = 1), (4) then implies that no assignment is possible as then the right hand side of (4) is zero. On the other hand, if the match *(ij)* is not selected *{y_{ij}* = 0) then this match can either be not assigned or assigned to at most one new match.

As for the new matches *(ij)eN,* each match can only be assigned at most to one of the existing exchangers. Hence the following constraint applies:

$$\sum_{(k,l) \in E_{ij}} z_{ij}^{(k,l)} \leq y_{ij} \qquad (i,j) \in N \tag{5}$$

where E_{ij} = *{(kJ)KM* e *E* such that M or *l=l*}.

Note that if the new match *(ij)eN* is not selected *(y^* 0), no assignment is made; if the new match is selected (y_{ij} = 1), it may be assigned at most to one of the existing exchangers.

Finally, to determine whether a new unit is actually required the following constraint can be written:

$$\mu_{ij} = y_{ij} - \sum_{(k,l) \in E_{ij}} z_{ij}^{(k,l)} \qquad (i,j) \in N \tag{6}$$

In this way for y_{ij} = 0 it follows from (5) that \iy = 0. If y»$_{ij}$• 1, then \L$_{ij}$ is either 0 or 1 depending on whether an existing exchanger is assigned or not to the particular match.

The objective function in (2) and the constraints (4) to (6) can then be incorporated within the following MILP assignment- transshipment model for determining the fewest structural changes in a network involving only one subnetwork:

$$\min \sum_{(i,j)\in E} y_{ij} + \sum_{(i,j)\in N} y_{ij} + \sum_{(i,j)\in N} w_{ij}\,\mu_{ij}$$

s.t. *constraints in (PO) for one subnetwork*

$$\sum_{k\in N(i)} z_{ik}^{(i,j)} + \sum_{k\in N(j)} z_{kj}^{(i,j)} \le 1 - y_{ij} \qquad (i,j)\in E$$

$$\sum z_{ij}^{(k,l)} \le y_{ij} \qquad (i,j)\in N$$

$$\mu_{ij} = y_{ij} - \sum_{(k,l)\in E_{ij}} z_{ij}^{(k,l)} \qquad (i,j)\in N \qquad (P1)$$

$$y_{ij} = 0,\ 1 \qquad (i,j)\in M$$

$$0 \le z_{ij}^{(k,l)} \le 1 \qquad (k,l)\in E_{ij}\ ,\quad (i,j)\in N$$

$$0 \le \mu_{ij} \le 1 \qquad (i,j)\in N$$

Note that in this formulation, the variables $z_{ij}^{(k,l)}$ and μ_{ij} are treated as continuous variables that are bounded between 0 and 1. The reason for this is that the assignment constraints in (4) and (5) imply integer values for $z_{ij}^{(k,l)}$ given a 0-1 value for y_{ij} (see Garfinkel and Nemhauser, 1972). As for μ_{ij} this variable can also be treated as continuous since it can only take 0-1 values from (6). Hence, an important advantage in problem *(P1)* is that it has the same number of binary variables as the grassroots model *(PO)*. The only major difference is the additional continuous variables $z_{ij}^{(k,l)}$, μ_{ij} and the additional constraints (4), (5), and (6).

From a qualitative point of view, problem *(P1)* will then determine those matches that maximize the use of existing units, and minimize first the introduction of new units and second the modification of existing units.

MODEL FOR MULTIPLE SUBNETWORKS

In many instances the minimum utility cost target involves one or more pinch points due to the use of more than one utility. This will then give rise to *NS* subnetworks where the most common procedure is to assign different units for the same stream match in the various subnetworks. In order to extend the MILP formulation *(Pi)* to the case when there is more than one subnetwork, K is convenient to define the set

S_r = {dmatch *{ij)* can potentially take place in subnetwork(s) *s]* *(ij)* e *M* (7)

Since very often many of the existing matches can take place in only one subnetwork, the set of existing matches *E* will be partitioned into two subsets:

Ef = {(*V)K*V)e ^{E} can only exchange heat in one subnetwork *re* S_{tJ}]

(8)

$E^{''m}$ *{QJ)KiJ)e* $^{E\,can}$ exchange heat in two or more subnetworks *se S^}*

In this way the set of matches for which an exchanger can be assigned involving the change in only one of the streams will be given by $N_A = N \cup E''$. That is, it is the set of non-existing matches as well as those existing matches that may require multiple heat exchange in the retrofit network. Similarly, as in the case of the previous section, the variables z ^\ i$P are introduced to denote the assignment of a match *(ij)* to another match *(ijc)* or *(kj)* that requires only one stream change at the subnetwork *s.* The main difference here is the fact that the existing matches *E* can be assigned to either the new matches *N* or to the matches *E"* that can take place in two or more subnetworks.

Consider first the matches *Ef.* Since these involve at most one unit in the retrofit network, their assignment constraint is similar to (4); that is,

$$\sum_{\substack{k \in N_A(i) \\ s \in S_{ik}}} \&ks \;\text{`-}\; I \sum_{\substack{k \in N_A(j) \\ s \in S_{kj}}} \%^{(i,i} \; £ \; 1 \; '' \; y_{ijr} \qquad '£\% \;,\; (iVOef \qquad (9)$$

where $N_A(i)$ = {set of cold streams *k* with which hot stream *i* can be matched for *(ijc) e N*}

A W = ($^{set\ of}$ tot streams *k* with which cold streamy can be matched for *(kj)eN}*

In other words, constraint (9) simply states that match *(ij)e &* can be assigned to a match in N_A if it is not included in the retrofit solution (y_{ijr} = 0).

To consider the assignment of a match *QJ)e* E", one has to decide on which of the new possible matches the existing unit might be assigned. To model this condition, one can define the 0-1 variable x_r which will indicate if any candidate match over the different subnetworks takes place. This variable x_r can be determined from the constraint

$$y_{ijs} \leq x_{i\}} \qquad seSij \ , \ (zV)€E" \qquad (10)$$

Note that if one y_{iLt} = 1, this implies that x„ • 1; if all y„ = 0 then x„ can take a zero value.

In order to assign the unit in *(ij)e E"* to a potential match in the different subnetworks, the following equation is included:

$$\sum_{seS_{tj}} z_{iis}^{(i,j)} = x_{ij} \qquad (i,j)\in E'' \qquad (11)$$

From (10) it is then clear that if one y_{ijs} = 1, this will imply that one assignment variable z^ will be forced to one. The assignment of match *(ij)e E"* to any match in N_A can then be written using the same idea as in (9), that is

$$\sum_{\substack{ke\ N_A(i) \\ seS^\wedge}} z_{iks}^{(i,j)} + \sum_{\substack{ke\ N_A(j) \\ seS_{kj}}} {}_{kjs}^{(i,j)} \qquad (i,j)\in E'' \qquad (12)$$

The set of matches in *N* can be treated the same as in (5),

$$\sum_{(We\ Eg} z£^\circ \leq y_{ijs} \qquad seSij \ , \ (iJ)eN \qquad (13)$$

where E_{tj} = {(kj)\(kj) € E such that k=i or /=/}.

The variables μ_{ijs} to denote the purchase and installation of new units are also similar to the ones defined in (6):

$$\mu_{ijs} = y_{ijs} - \sum_{(k,l)\in E_{ij}} z£^\circ \qquad s\in S_{ij} \ , \ (i,j)\in N_A \qquad (14)$$

Note that in this case, the variables μ_{ijs} are defined for the potential matches in the set N_A.

From equations (9) to (14) and using a similar definition for the objective function as in (2), the MILP assignment- transshipment model for predicting the matches in multiple subnetworks is given by:

$$\min \sum_{\substack{(i,j)\in E' \\ r\in S_{ij}}} \varepsilon\, y_{ijr} + \sum_{\substack{(i,j)\in E'' \\ s\in S_{ij}}} \varepsilon\, z_{ijs}^{(i,j)} + \sum_{\substack{(i,j)\in N \\ s\in S_{ij}}} y_{ijs} + \sum_{\substack{(i,j)\in N_A \\ s\in S_{ij}}} W\, \mu_{ijs}$$

s.t. constraints in (P0) for NS subnetworks

$$\sum_{\substack{k\in N_A(i) \\ s\in S_{ik}}} z_{iks}^{(i,j)} + \sum_{\substack{k\in N_A(j) \\ s\in S_{kj}}} z_{kjs}^{(i,j)} \le 1 - y_{ijr} \qquad r\in S_{ij}\ ,\ (i,j)\in E'$$

$$y_{ijs} \le x_{ij} \qquad s\in S_{ij},\quad (i,j)\in E''$$

$$\sum_{s\in S_{ij}} z_{ijs}^{(i,j)} = x_{ij} \qquad (i,j)\in E''$$

$$\sum_{\substack{k\in N_A(i) \\ s\in S_{ik}}} z_{iks}^{(i,j)} + \sum_{\substack{k\in N_A(j) \\ s\in S_{kj}}} z_{kjs}^{(i,j)} \le 1 - x_{ij} \qquad (i,j)\in E''$$

$$\sum_{(k,l)\in E_{ij}} z_{ijs}^{(k,l)} \le y_{ijs} \qquad s\in S_{ij}\ ,\ (i,j)\in N \qquad (P2)$$

$$\mu_{ijs} = y_{ijs} - \sum_{(k,l)\in E_{ij}} z_{ijs}^{(k,l)} \qquad s\in S_{ij}\ ,\ (i,j)\in N_A$$

$$y_{ijs} = 0,\ 1 \qquad s\in S_{ij}\ ,\ (i,j)\in M$$

$$0 \le z_{ijs}^{(k,l)} \le 1 \qquad (k,l)\in E_{ij}\ ,\ s\in S_{ij}\ ,\ (i,j)\in N_A$$

$$0 \le x_{ij} \le 1 \qquad (i,j)\in E''$$

$$0 \le \mu_{ijs} \le 1 \qquad s\in S_{ij}\ ,\ (i,j)\in N_A$$

Note that problem *(P2)* has only y_{ij} as the binary variables, since z£°, x_{ij} and H17. can be treated as continuous variables due to the special structure of the assignment constraints (9) to (14). It should also be noted that in general, problem *(P2)* must be solved simultaneously for all the subnetworks due to the coupling of the variables x_{ij} in constraints (10), (11), and (12). Furthermore, one can easily verify that for the case of only one subnetwork, *NS* - 1, problem *(P2)* reduces to problem *(Pi)* as then *E* = *E*\ £"=0, and $N_A=N$.

As a final point, it should also be noted that when two or more subnetworks are present another alternative is to apply formulation *(Pi)* so as to consider the case when only one unit is used per match even if it crosses the pinch point. This, however, will tend to increase the area requirements and complicate the piping as noted in Wood et al. (1985). As discussed by these authors, this alternative can be attractive if the composite heating and cooling curves are nearly parallel.

The next section will illustrate the application of *(PI)* and *(P2)* in two example problems.

EXAMPLE PROBLEMS

EXAMPLE 1: ONE SUBNETWORK RETROFIT DESIGN

The existing network shown in Figure 1 consists of seven units involving three hot streams and three cold streams, and one hot and one cold utility (see Table 1 for stream data). The utility cost of this network is $44,800/year. By performing a minimum utility cost calculation with the LP transshipment model and assuming 10 K for the minimum temperature approach, it is found that only 440 kW of the cold utility are required at the annual cost of $8,800/year. Hence there is a clear incentive to consider the retrofit design of the network.

Since the minimum utility cost can be achieved in a single subnetwork as there is no pinch point, the MILP formulation (^1) can be applied to predict the required structural changes in the network. The MILP assignment- transshipment model involves 12 binary variables for the matches, 53 continuous variables and 49 constraints. Of the continuous variables, 25 of them correspond to assignment variables and variables to denote new units. Of the 49 constraints, 18 of them correspond to the additional constraints (4) to (6). The values of the weights in *(PI)* were set to e = 0.01 and *W* = 100.

The MILP model *(PI)* was solved with the computer code LINDO requiring 4.2 seconds of CPU time on a DEC-20. As can be seen in Table 2, a total of 6 matches are predicted by this model. Of these 6 matches, 4 of them correspond to existing units, while 2 of them (H1-C1, H2-C3) are new matches that can be obtained by reassigning two existing units that are not needed in the retrofit network. Note that matches H1-C2, H2-C3 (modified from H1-C3), and H3-C1 require the same heat loads as their corresponding matches in the existing network.

The actual retrofit network was derived manually based on the information in Table 2, and is shown in Figure 2. Note that the modifications involved in the piping are not very extensive. Also as noted in Figure 2, exchangers 1 (H1-C2) and 7 (H1-C1) require additional area (87.5 m^2 and 31.21 m^2, respectively), while exchangers 2, 5 and 6 require less area. The first two would clearly require the installation of additional area, while the last three may simply require the use of bypasses or tube-plugging.

Figure 3 presents an alternative retrofit design for the same matches predicted in Table 2. In this design the service of exchangers 6 and 7 is switched by the use of a more involved repiping scheme. As shown in the table of Figure 3, this drawback is compensated by the fact that less additional area is required (88.54 m^2 versus 118.71 m^2 in Figure 2). A detailed economic analysis is clearly needed to resolve this trade-off between changes in area and changes in piping.

Finally, Figure 4 presents a near optimal grassroots network design that was obtained for the stream data in Table 1. Note that this network involves 5 new matches with respect to the existing network. It is clear that this solution is of not much help for evolving towards the retrofit designs shown in Figures 2 and 3. In addition, it should be noted that the total area in the grassroots network of Figure 4 is 186.3 m^2 while the total effective area of the retrofit networks in Figures 2 and 3 is 203.1 m^2 (9% higher). As expected, there is no reason to believe that the area of retrofit designs will be very close to the one of the grassroots design.

EXAMPLE 2: TWO SUBNETWORK RETROFIT DESIGN

The existing network shown in Figure 5 involves 5 units with two hot and two cold process streams and one hot and one cold utility (see stream data in Table 3). The utility cost for the steam and cooling water is $158,000/year.

Assuming a 10 K minimum temperature approach, the minimum utility target leads to an annual cost of only $28,000/year since the steam consumption can be reduced from 1500 kW to 200 kW, while the load of the cooling water can be reduced from 1900 kW to 600 kW. The pinch point for this utility target is 363-353 K, and hence two subnetworks must be considered.

In order to predict the required structural changes of the network in Figure 5, problem *(P2)* was formulated. The MILP model involves 10 binary variables, 33 continuous variables, and 39 constraints. The values of the weights were set to e = 0.01 and *W* • 100. The solution of this problem required 1.2 seconds CPU-time (DEC-20) with the computer code UNDO.

As seen in Table 4, a total of 6 matches were predicted for the retrofit network. Of these, 3 correspond to existing matches, 2 are modifications of existing units (H2-C1, S1-C1), and one is a match requiring a new unit (H1-C2). Based on this information, the configuration of the retrofit network was derived manually and is shown in Figure 6. As can be seen, a relatively modest amount of piping change is required. Also, only the area of exchanger 1 has to be increased (by 22 m^2) in addition to the purchase of exchanger 6 (165 m^2).

For comparison, Figure 7 presents a retrofit design that is based on a manual readjustment of a new optimal grassroots design. It can be clearly seen that apart from a much more complex repiping scheme, this design retains only two existing exchangers, while requiring 3 modified units and one new unit. In addition, the extra area needed is larger than that of the retrofit network in Figure 6 (30.4 m^2 versus 22 m^2). Hence the solution obtained in Figure 6 is clearly superior.

Finally, it is interesting to note from Figure 5 that exchanger 3 is the only one that crosses the pinch point (363-353 K). If one were to follow the guidelines by Tjoe and Linnhoff (1986), one would remove this exchanger. However, as shown in Figure 6, this is actually not necessary. By reassigning the matches in this network according to the proposed formulation, the temperatures of this exchanger are modified in such a way that it will lie below the pinch point. Hence, this example then shows that the guideline of removing matches that cross the pinch point might not always be valid due to the interactions with other possible retrofit modifications.

CONCLUSION

In this paper, an MILP assignment- transshipment model has been proposed for the structural retrofit of HEN's. Given a desired level of heat recovery, the objective of the model is to find a retrofit structure which first minimizes the need for new exchanger units and then minimizes the reassignment of existing units. The formulation can be viewed as an extension of the grassroots transshipment model proposed by Papoulias and Grossmann (1983). The extension involves a new objective function that takes into account the existing network and penalizes structural network changes. In addition, a set of assignment constraints and variables is included to allow for possible reassignment of existing exchangers to new hot stream/cold stream matches. The proposed formulations can be applied to networks with one or more subnetworks.

It is noted that due to the structure of the added constraints in the proposed model, all the assignment variables can be treated as continuous variables and still retain the required integer values. As a result of this, the computational effort for the assignment- transshipment model does not differ much from that of the grassroots MILP transshipment model.

The application and usefulness of the MILP assignment- transshipment model have been shown in two examples. The results show that the proposed model can identify in a systematic manner the fewest number of structural modifications in an existing network with very modest computational times. The results also point to the fact that some of the general retrofit guidelines provided in literature may fail. The removal of a match which crosses a pinch point ,as suggested by Tjoe and Linnhoff (1986), was found not necessary in one example.

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Table 1. Stream Data for Example 1

Stream	Fc_p Flowrate (kW/K)	T_{in} (K)	T_{out} (K)	Cost ($/kW-yr)
H 1	10	500	350	–
H 2	12	450	350	–
H 3	8	400	320	–
S 1	–	540	540	80
C 1	9	300	480	–
C 2	10	340	420	–
C 3	8	340	400	–
W 1	–	300	320	20

$U = 0.8\ kW/(m^2 K)$

Table 2. Predicted Matches for the Retrofit of Example 1.

(a) Matches and Heat Loads (kW) (Existing Network/Retrofit Network)

hot^^|tream strearn^V^	C1	C2	C3	W1
H1	— /700	800/800	480/—	220/—
H2	620/280		— /480	580/440
H3	640/640			
S1	360/—			

(b) Matches for Retrofit Network

Existing Matches: H1-C2, H2-C1, H2-W1, H3-C1

New Matches: H1-C1 unit assigned from S1-C1
H2-C3 unit assigned from H1-C3

Table 3. Stream Data for Example 2

Stream	Fbp Flowrate (kW/K)	Tin(K)	Tout W	Cost ($/kW-yr)
H1	30	443	333	—
H2	15	423	303	—
S 1	—	450	450	80
C1	20	293	408	—
C2	40	353	413	—
W1	—	293	313	20

$U = 0.8\ kW/(m^2\ K)$ for all exchanges except ones involving S1

$U - 1.2\ kW/(m^2\ K)$ for exchanges involving S1

Table 4. **Predicted Matches for the Retrofit of Example 2.**

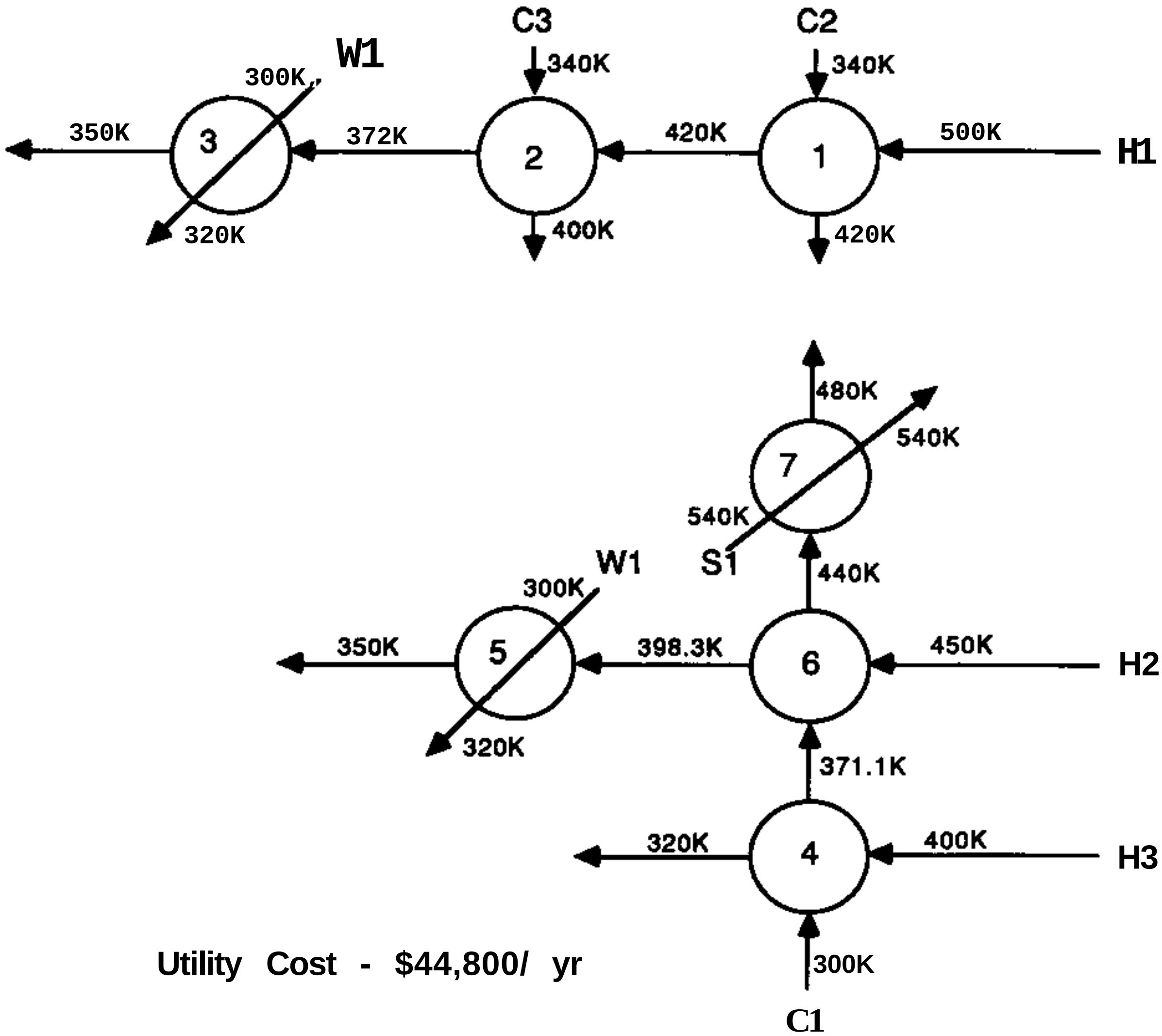
(a) Matches and Heat Loads (kW) (Existing Network / Retrofit ™ ITnZII 2[1] >

hotV^tream strearn^V^	C1	C2	W1
H1	1400/ 37o	— /.2400	1900/6^0
H2	900/HI	900/ I	
S1	— /, 200	1500/ Z	

(b) Matches for Retrofit Network

Existing Matches: H1-C1 (Subnetwork 2)
H1-W1 (Subnetwork 2)
H2-C1 (Subnetwork 2)

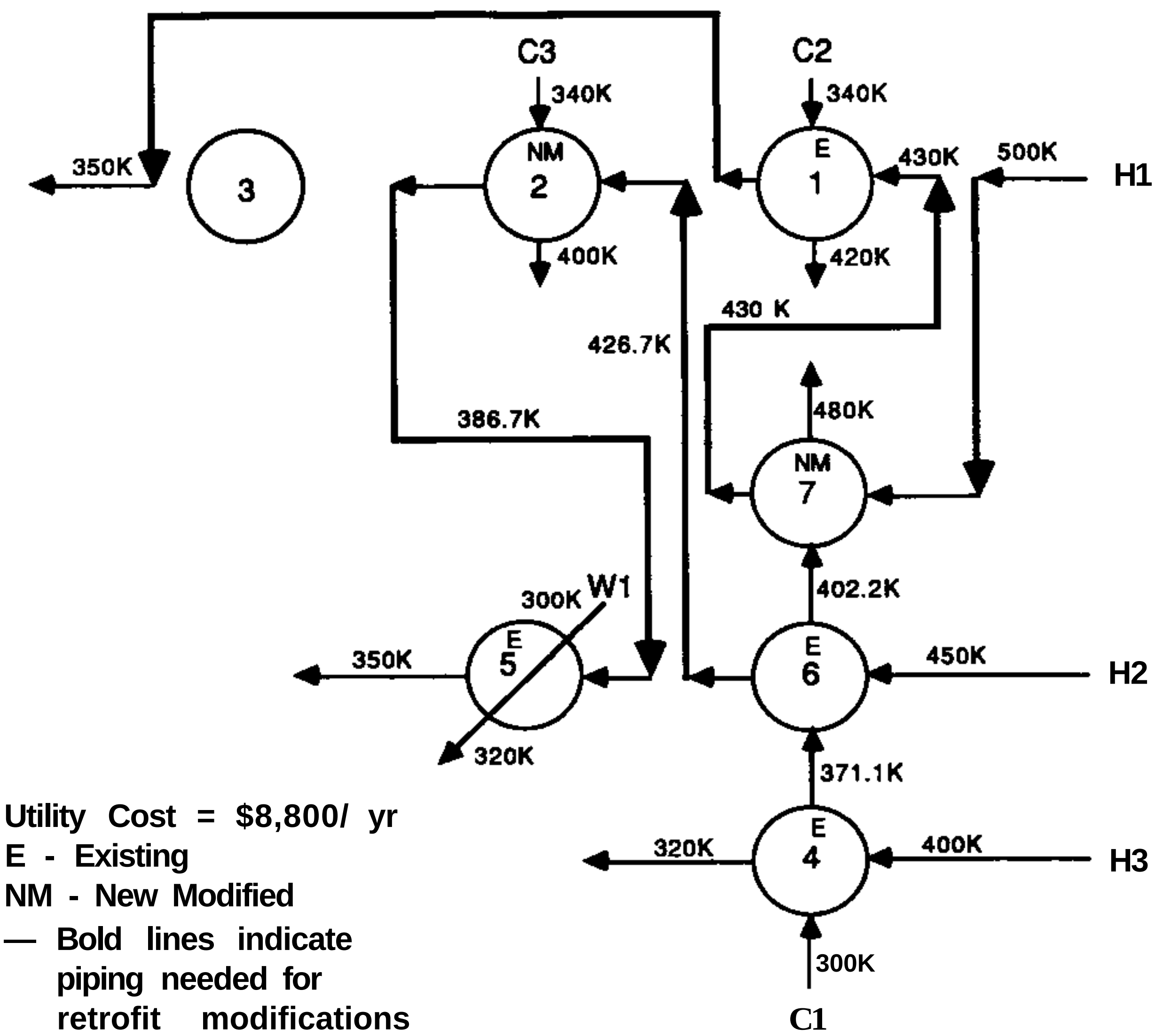
New Matches: S1-C1 (Subnetwork 1) unit assigned from S1-C2
H2-C1 (Subnetwork 1) unit assigned from H2-C2
H1-C2 (Subnetwork 1) new unit



Utility Cost - $44,800/ yr

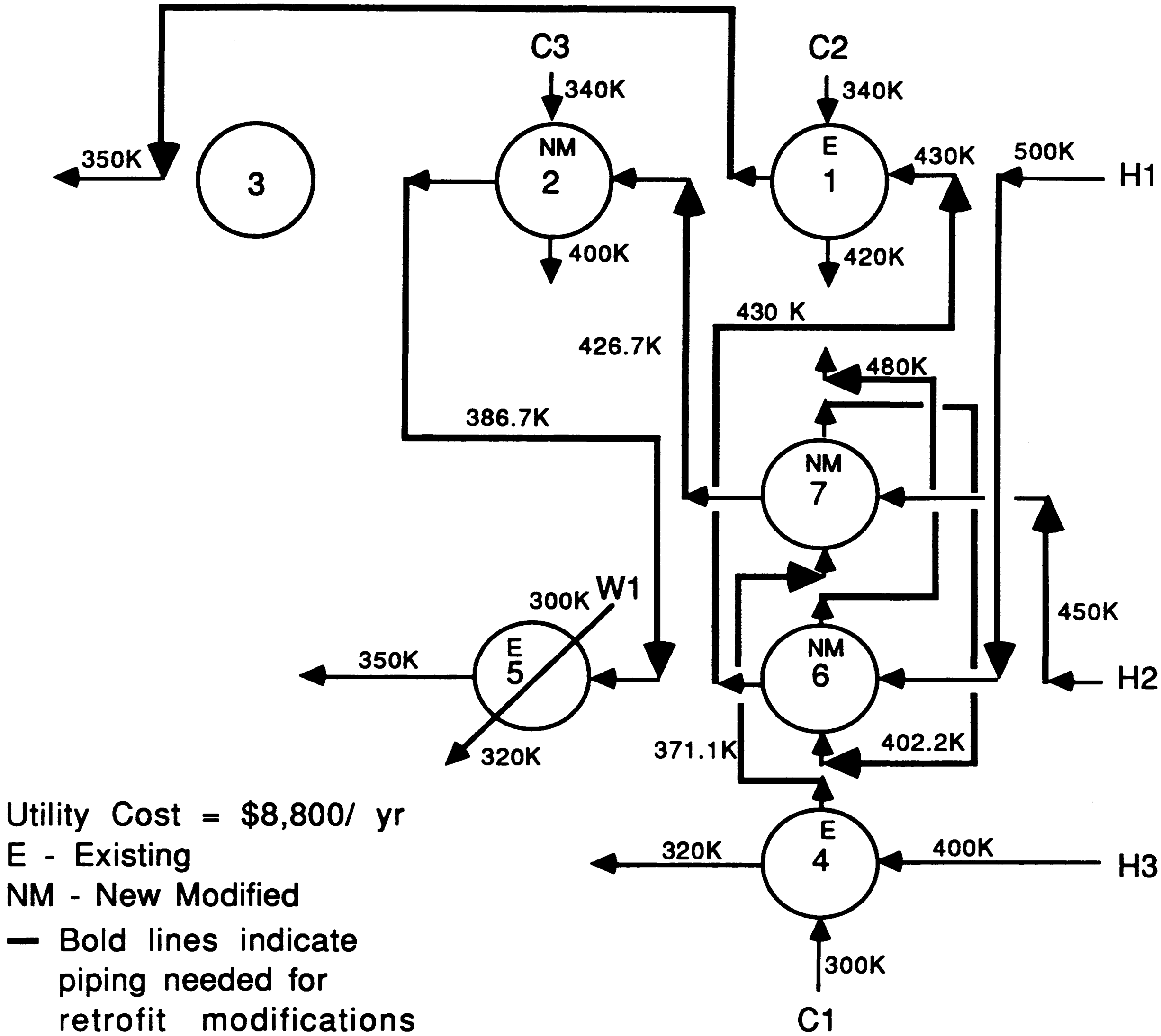
Exchanger	Area (m^2)	Heat Load (kW)
1	12.50	800
2	23.50	480
3	5.39	220
4	33.09	640
5	11.49	580
6	45.06	620
7	5.75	360

Figure 1: Existing Network for Example 1.



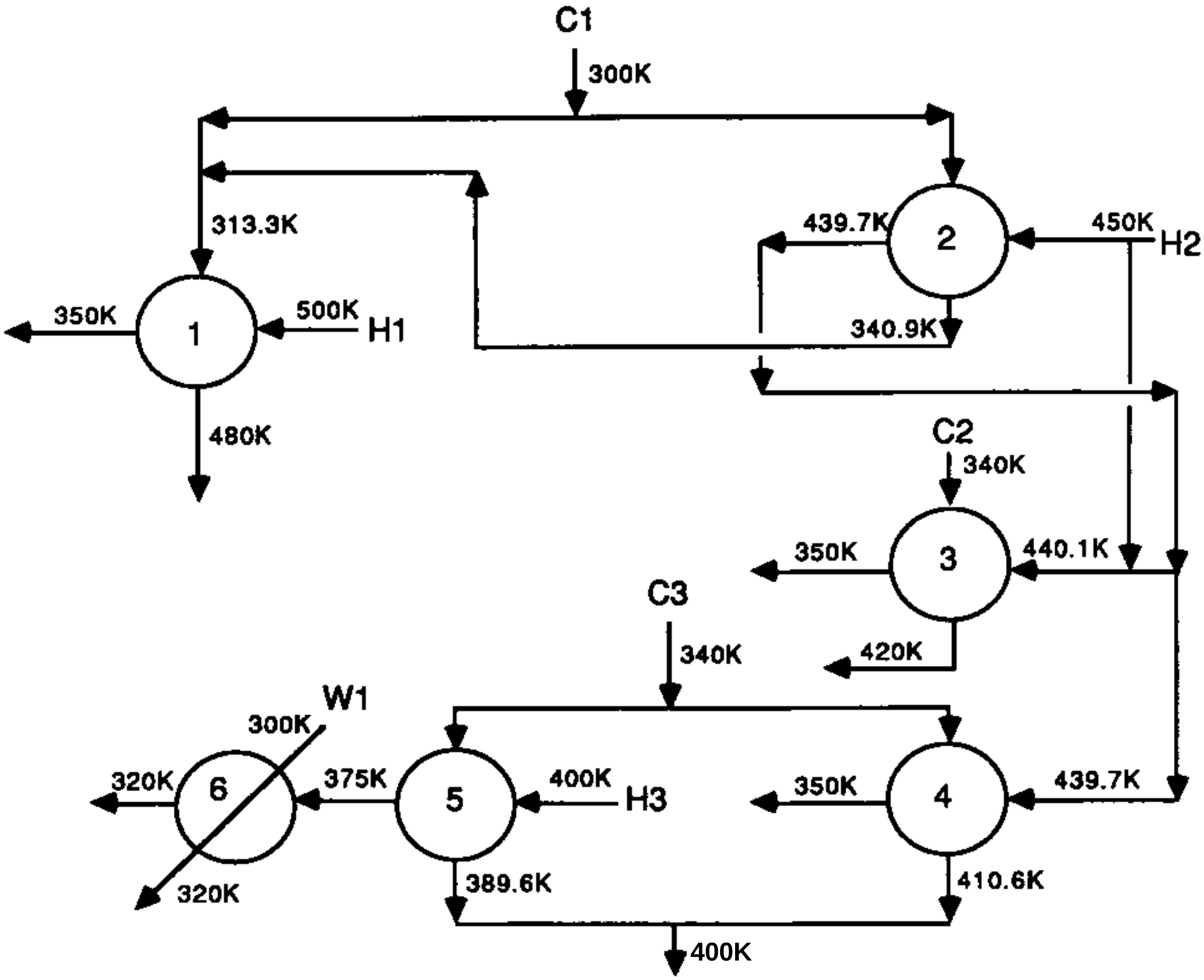
Exchanger	Existing Area (m^2)	Retrofit Area (m^2)	Area Change Needed (m^2)	Heat Load (kW)
1	12.50	100.0	+87.5	800
2	23.50	16.79	-6.71	480
4	33.09	33.09	0	640
5	11.49	9.49	-2.00	440
6	45.06	6.79	-38.27	280
7	5.75	36.96	+31.21	700

Figure 2: Retrofit Network 1 for Example 1.



Exchanger	Existing Area (m^2)	Retrofit Area (m^2)	Area Change Needed (m^2)	Heat Load (kW)
1	12.50	100.0	+87.5	800
2	23.50	16.79	-6.71	480
4	33.09	33.09	0	640
5	11.49	9.49	-2.00	440
6	45.06	36.96	-8.10	700
7	5.75	6.79	+1.04	280

Figure 3: Retrofit Network 2 for Example 1.

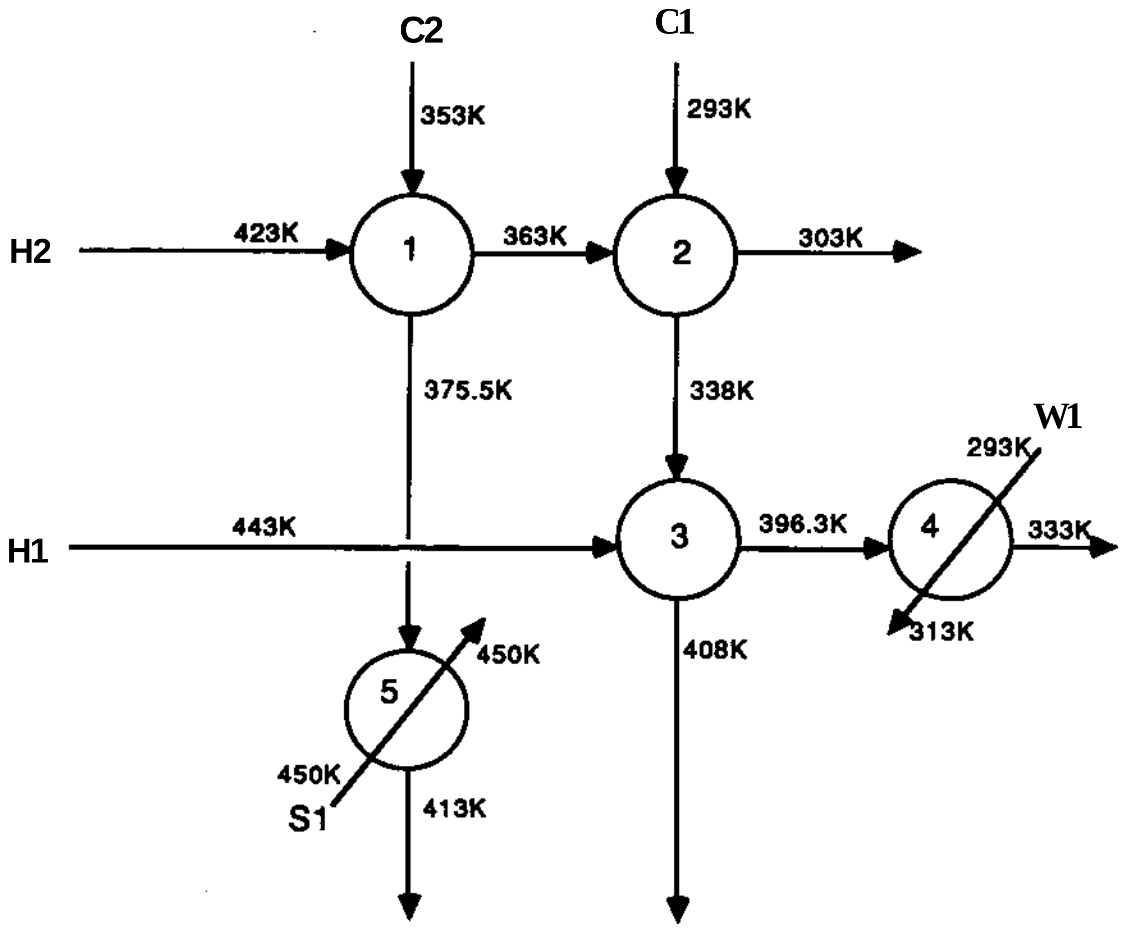


Utility Cost = $8,800/ yr

Exchanger	Area (m^2)	Hot Stream Fcp (kW/K)	Cold Stream Fcp (kW/K)	Heat Load (kW)
1*	68.19	10.0	9.0	1500
2	1.21	11.62	2.91	119.5
3*	69.09	8.87	10.0	799.5
4*	19.57	3.12	3.96	279.5
5*	12.32	8.0	4.03	199.9
6*	15.89	8.0	—	440

* New Matches comparing to Existing Network

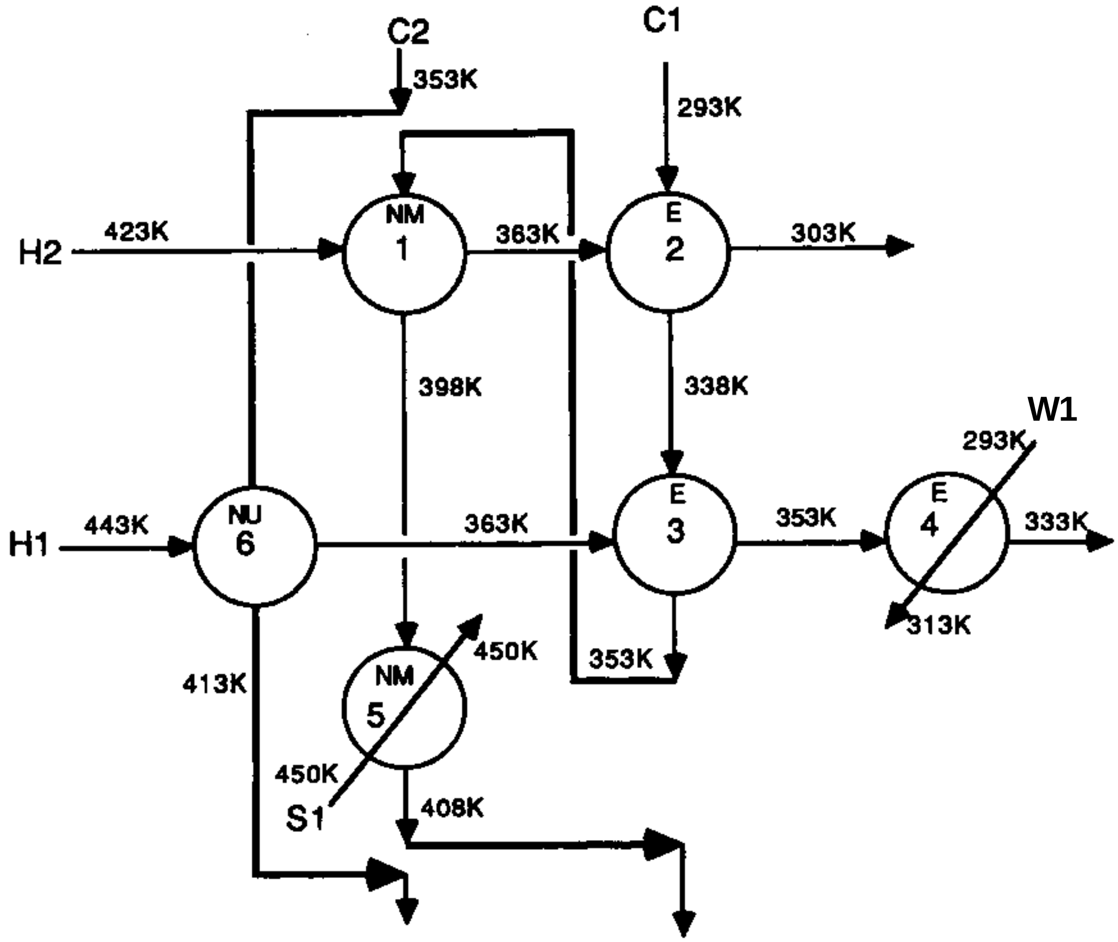
Figure 4: Grassroots Network for Example 1.



Utility Cost « $158,000/ yr

Exchanger	Area (m^2)	Heat Load (kW)
1	46.74	900
2	68.72	900
3	38.31	1400
4	40.23	1900
5	23.33	1500

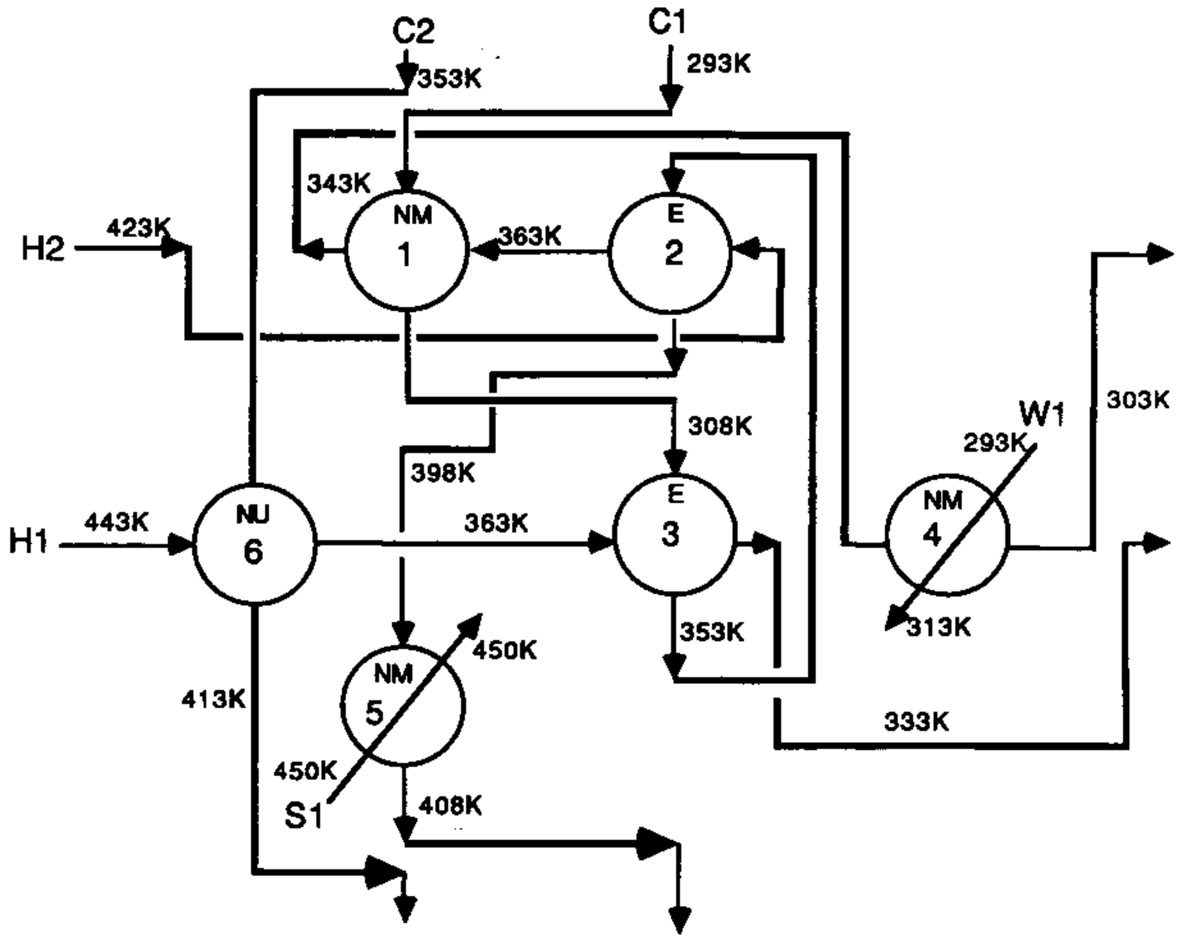
Figure 5: Existing Network for Example 2.



Utility Cost = $28,000/ yr
E - Existing
NM - New Modified
— Bold lines indicate piping needed for retrofit modifications

Exchanger	Existing Area (m^2)	Retrofit Area (m^2)	Area Change Needed (m^2)	Heat Load (kW)
1	46.74	68.72	+21.98	900
2	68.72	68.72	0	900
3	38.31	30.41	-7.90	300
4	40.23	18.75	-21.48	600
5	23.33	3.56	-19.77	200
6	0	164.79	—	2400

Figure 6: Retrofit Network for Example 2.



Utility Cost = $28,000/ yr
E - Existing
NM - New Modified
— Bold lines indicate piping needed for retrofit modifications

Exchanger	Existing Area (m^2)	Grassroots Area (m^2)	Area Change Needed (m^2)	Heat Load (kW)
1*	46.74	7.15	-39.59	300
2	68.72	68.72	0	900
3	38.31	68.72	+30.41	900
4*	40.23	41.20	+0.97	600
5*	23.33	3.56	-19.77	200
6*	0	164.79	—	2400

* New Matches comparing to Existing Network

Figure 7: Retrofit Network for Example 2 based on Grassroots Design