Diagnosis and Optimization Approach for Heat Exchanger Network Retrofit

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A new modeling approach for HEN retrofit design is discussed. The design task consists of a search for topology changes, called the diagnostic stage, followed by an evaluation stage and a cost optimization stage. Promising modifications are selected from the diagnosis stage and assessed in terms of the impacts on implementation cost, operability, and safety. The options deemed impractical are removed and the remaining ones are optimized together with the existing HEN to give the final HEN retrofit design. The new approach combines mathematical optimization techniques with a better understanding of the retrofit problem, based on thermodynamic analysis and practical engineering, to produce a systematic procedure capable of efficiently solving industrial-size retrofit problems. The network pinch concept provides new insights to the HEN retrofit problem and plays an important role in selecting promising modifications, forming the foundation of the new method. This concept, when applied to mathematical formulation, significantly simplified the mathematical models while maintaining good quality of solutions. This approach allows the design tasks to be automated with user interactions.

Introduction

Most process plants undergo at least one major revamp in their lifetime to take advantage of advances in process technology, to improve energy efficiency, or to increase the plant production rate. During such revamps, retrofit of the process heat exchanger network (HEN) is normally required to ensure that required processing temperatures are attained under the new operating conditions. Several alternative designs, with varying capital and operating costs, need to be produced to satisfy the new operating requirements, and the final retrofit design must be selected from these alternatives. As the retrofit HEN design can significantly affect the economics of the overall project, the identification of the most cost-effective design is an important aspect of the design task. The alternative designs may also vary in operability, flexibility, and inherent safety, and these factors must also be considered in the determination of the final retrofit HEN design.

Only a few methods for HEN retrofit design have been proposed. Methods proposed for retrofit HEN design may be subdivided into two groups. The first group of methods are those based on ''pinch techniques'' (Tjoe and Linnhoff, 1986; Polley et al., 1990; Shokoya and Kotjabasakis, 1991; Carlsson et al., 1993). The second group of methods are those based on the use of mathematical programming techniques (Jones et al., 1986; Saboo et al., 1986; Ciric and Floudas, 1990; Yee and Grossmann, 1991). These two groups of methods have evolved separately with little interaction between them.

Three stages of design approach are adopted in the pinch methods. The first stage is the so-called targeting stage, which determines the optimal level of heat recovery. For the heat recovery fixed at the optimal level, promising modification options are then identified, which intend to correct existing criss-cross heat-transfer exchangers. Finally, the network is evolved to reduce the total cost. The optimality of the optimal level of heat recovery is questionable since it is determined by only trading off additional surface area against energy saving. In reality, implementation costs including piping cost can be very significant comparing the capital cost for additional area. The second problem associated with pinch methods is that many modifications usually appear in a retrofit design. As a consequence, the evolution of the design to reduce the number of modifications becomes necessary, which is a difficult task. Finally, pinch design methods are

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essentially manual in nature. Although this places the designer in control throughout the design process, the manual nature of pinch methods means that the design process can at times be time-consuming and tedious and the designer must be conversant with the design methods.

For the methods using mathematical programming techniques, the common feature is that a retrofit design problem is formulated as an optimization problem in which a general superstructure is constructed including all possible changes to the existing network. This superstructure is subject to total cost minimization, which gives the optimal retrofit design as a result. The potential problem is that the number of combinations of different modification options embedded in a general superstructure can be prohibitively large. This may cause both mathematical and computational difficulties in solving the optimization problem. The challenge in defining a superstructure is therefore to minimize the number of infeasible and uneconomic solutions included in the solution space without omitting any promising solutions.

To consider the modification costs, mathematical programming methods attempt to directly address the implementation costs including piping costs and installation costs for different modifications. Thus, these methods require that implementation costs for every potential topology change be provided in advance of the design. As there are a large number of potential topology change options included in a superstructure, estimating modification costs for all these options becomes an impractical and unmanageable task. Any inaccuracy in the costs provided would invalidate the results obtained. On the other hand, cost is only one of the factors, which influence the selection of modifications and designs. Other factors, such as safety and operability, play an important role in the selection of designs. These factors are qualitative in nature, and although they cannot be expressed explicitly, they must be traded off against other design requirements. This underlines the importance of user interaction in retrofit design, as this provides the mechanism for the designer to influence the design process with his perception of relative qualitative considerations.

In summary, there are three challenges for research into developing practical HEN retrofit design methods. The first challenge arises from very expensive modification costs, which are considered improperly in current methods. Therefore, it becomes very desirable for a method to be able to consider modification costs but without the impractical requirement of having to estimate modification costs for all potential options prior to design. Secondly, it is important for a design method to allow for both automated and interactive generation of retrofit design. The automation of a design process can save engineering time dramatically, while interaction allow users to assess modifications on a much wider basis including qualitative aspects. The third challenge is how to control the size of the retrofit optimization problem and, thus, make it possible to solve large industrial problems.

Problem Statement

The HEN retrofit problem to be solved in this article is stated as follows. Given are a set of hot streams and a set of cold streams with their supply and target temperatures, heat capacity flow rates, and heat-transfer coefficients. Given also include the data for existing individual heat exchangers (such as types and surface area), and their connections. It is given the current use of utilities by the existing HEN and available utilities for heating and cooling. It is also given the costs for additional area. Several objectives can be specified, and these include minimization of capital investment for a fixed heat recovery, and minimization of the total cost (investment and operating costs). While considering these objectives, the constraints for safety and operability must be satisfied as well. Some comments about this problem statement are given as follows.

Piping structure and costs

As explained previously, it is a very tedious task to figure out the detailed piping structures for all potential modifications. In this work, it is not required to provide piping cost estimates for all possible modifications prior to design. It will become clear later that only relevant piping information will be required to help the selection of modifications.

Structure changes

Three types of structural changes to a HEN are considered, namely relocation (change to the pairing of two streams in an exchanger and/or to the sequence of exchangers), stream splitting (placing existing exchangers in parallel), and addition of new exchangers.

Stream segments

The heat capacities of process streams are often temperature-dependent, and, in such cases, they cannot be realistically assumed to have constant heat capacities. As an alternative to the use of temperature-dependent heat capacities, streams are often subdivided into a number of constant heat capacity segments. In this way the variation in the heat capacity of the stream is approximated by piecewise constant heat capacities. However, stream segments cannot be treated in the same way as individual streams. Otherwise, it is not possible to predetermine the segment on which any particular exchanger will be located, and some exchangers in the network may be located across more than one segment. Currently, no methods for HEN design can handle segmented streams effectively. This limits their applicability, because segmented streams occur in many industrial HEN design problems. The method presented in this article can, however, comprehensively deal with all aspects of stream segments.

Variable utilities

It can be beneficial to retrofit a HEN by changing the current use of utilities by adding new utility exchangers, switching utilities, and changing the utility loads in existing utility exchangers. These modifications are considered together with the utility system. There is no assumption made in this work for the location of utility heat exchangers. They can be located in any place of a HEN.

Process conditions

It is assumed in this work that processes conditions (such as temperatures, pressures, and flow rates) are fixed when retrofitting a HEN. Usually, process changes are considered before HEN retrofit.

Thermodynamic consideration

It is first recognized by Asante and Zhu (1997) that the bottleneck for an existing HEN should be described by the concept of the *network pinch* instead of the process pinch (Linnhoff et al., 1982). The process pinch is defined by process conditions (stream temperatures and heat capacity flow rates), and it does not reflect the structure of an existing HEN. With this improved understanding, the network pinch concept is used for guiding the selection of modifications. Application of this concept results in a great simplification of the HEN retrofit problem. The detailed discussions are given below.

Pinch Matches and Network Pinch

Definition

In most cases, the heat recovery achieved in a HEN can be increased by the addition of surface area to some exchangers in the network. However, when area is added without altering the HEN topology, the heat recovery can be increased by a certain amount beyond which any further addition of area will not improve heat recovery. This suggests the presence of a heat recovery limit within the HEN topology, which is independent of the area of individual exchangers in the network.

It has been shown (Asante and Zhu, 1997) that every heat exchanger network structure has a maximum heat recovery limit, which is a characteristic of the network structure. This limit to heat recovery is caused by *pinch matches* (matches that tend towards a limiting temperature driving force as the heat recovery achieved in HEN is increased). In addition, as their driving forces get smaller, the area required by these pinch matches increases exponentially. Pinch matches are, therefore, a very important characteristic of HEN structures, as they identify a bottleneck to heat recovery and also affect the area requirement of the network. This bottleneck is termed as the *network pinch*.

The network pinch defines the heat recovery limit of a given HEN topology and process for a given exchanger minimum approach temperature (EMAT) in the HEN. It also divides the HEN into a heat deficient sink and a source in heat surplus in a manner analogous to the process pinch (Linnhoff et al., 1982). The main difference between the network and process pinches, however, is that the network pinch is a characteristic of both the process streams and the HEN topology, while the process pinch is a characteristic of the process streams alone. Consequently, changes in the topology of a process HEN may affect the network pinch, but will always leave the process pinch unchanged. Although the process and network pinch locations may coincide, they are usually distinct and different.

Uniqueness of the network pinch location

It must be noted that when a HEN topology is at its maximum heat recovery potential (R_{max}), it may be possible to shift heat around some of the loops in the HEN. This means that the loads of all exchangers in the HEN may not be fixed at the network heat recovery limit. As a direct consequence of this, the number of pinching matches in a HEN at its heat recovery limit may sometimes be varied. This is illustrated by the HEN in Figure 1, which shows a HEN at its heat recovery limit.

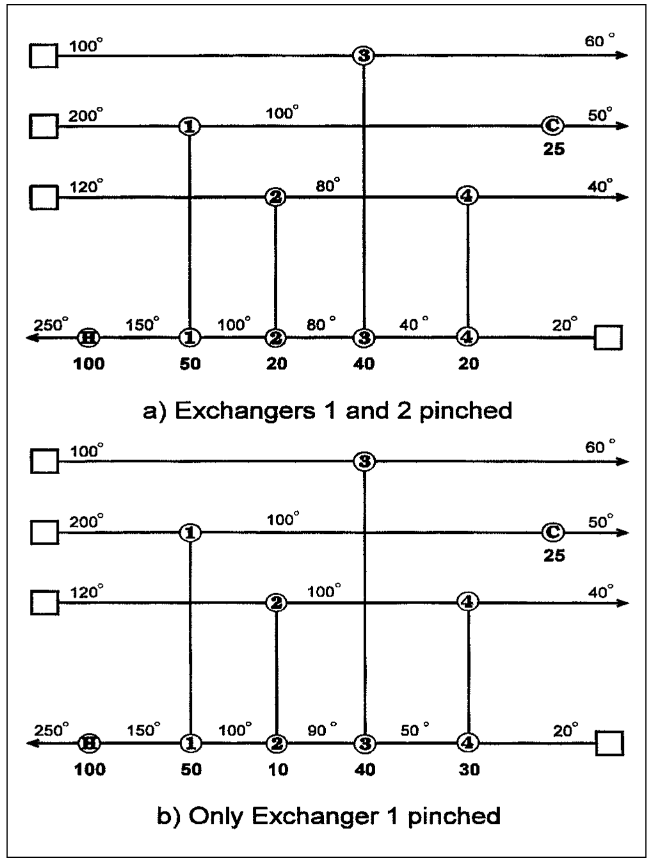

Figure 1. Example HEN at its heat recovery limit.

Exchangers 2 and 4 in this HEN form a loop around which heat can be shifted without altering the HEN heat recovery. Consequently, depending on how heat is shifted around the loop, either both exchangers 1 and 2 will be pinched (as shown in Figure 1a), or only exchanger 1 will be pinched (as shown in Figure 1b). In both cases, however, the heat recovery of the HEN remains at the maximum limit of 130 kW.

It is important to note that only exchanger 1 is a pinching match, because the definition of pinching matches excludes "pinched" exchangers whose limiting driving force can be relaxed by shifting heat around a loop in the HEN. In order to correctly identify the pinching matches in a HEN, it is, therefore, necessary to ensure that only genuine pinching matches are identified, and this can be achieved by minimizing the number of pinching matches in the HEN. Note that for simplicity, a zero value of EMAT is used in the above example. In reality, a practical EMAT should be used for identification of pinch matches.

Significance of the network pinch concept

• The network pinch identifies the limit (bottleneck) inherent in an existing network, and it, therefore, indicates the requirement of topology changes to an existing HEN. In other words, when a HEN reaches its network pinch limit (or heat recovery limit), the only way to overcome it is to alter the topology of the HEN if no process changes are considered.

• The network pinch concept provides guidance for selecting topology changes. It has been realized that not all topology changes produce a positive impact on overcoming the network limit (bottleneck). The thermodynamic principle introduced by Asante and Zhu (1997) for identifying beneficial topology changes is that they must move heat from below to above the network pinch. This principle provides a valuable means of screening out those topology changes, which cannot improve the heat recovery of a network. This principle greatly simplifies the optimization problem.

Selection of Topology Modifications

In most cases, many topology change options capable of overcoming the network pinch can be identified and usually they produce different impacts towards costs and savings. In order to select the best topology change option among many alternatives, it is necessary to define a measure of optimality, which is independent of the heat recovery level at which the network will finally be designed. This is because it is impossible to reliably identify the ''optimal'' heat recovery level for a retrofit design, prior to the identification of the topology changes involved (as these have a major impact on the economics of the network design). A cost-based objective cannot be employed for this purpose, as it can only measure the cost of a network at a specified heat recovery level. Furthermore, if the total cost is used as the criteria for selecting topology changes, the costing information for piping, labor, installation, and so on, for all potential change options would be required prior to design, which can be a very tedious task as mentioned above.

As an alternative to cost-based objectives, the maximization of the heat recovery potential can be used as an optimization objective for selection of topology change options. The heat recovery potential is a property of the network, and provides a quantitative measure of the network pinch (or bottleneck) of a given network structure. This is further illustrated in Figure 2. Different topology changes feature different trade-offs between heat recovery and area requirement.

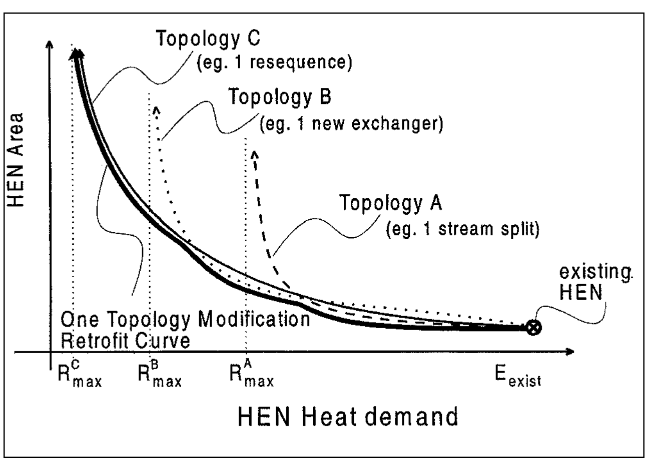

Figure 2. One-topology modification retrofit curve.

The optimal topology modification retrofit curve would, by definition, form a lower bound to all the topology specific curves. It can be seen from this figure that the topology specific curve, which deviates least from the optimal topology modification retrofit curve, is the one with the largest heat recovery potential (such as topology change C in this figure). This provides the justification for the use of maximization of heat recovery potential as an optimization objective for selection of topology changes. It must be emphasized that the selected topology will not be ''optimal'' at every heat recovery level, because no single topology option could fulfill such an objective. The selected topology, however, provides the best trade-off between area and recovery over the feasible heat recovery range.

Therefore, in the stage of selecting topology modifications, the maximization of heat recovery potential is defined as the objective function. Although this objective function provides good measure for area-energy trade-off, it does not, however, account for the cost of topology change itself. Each topology selected must, therefore, be examined in the evaluation stage to ensure that the energy and area savings it provides justify its implementation costs.

Remarks for the selection criteria

As cost minimization is not sought in the stage of selecting change options, the resulting design cannot be guaranteed to be the minimum cost retrofit design. However, the selection criterion ensures the generation of low cost retrofit designs, because each modification selected is also geared towards improving the trade-off between additional area and energy saving. More importantly, the criterion tends to minimize the number of topology changes used to achieve any heat recovery target by maximizing the heat recovery potential from each topology change. As the retrofit cost is often dominated by the cost of topology changes, this helps to reduce the overall retrofit cost.

Another benefit of using this selection criterion is that it separates the selection of topology changes from the rest of HEN retrofit design on an inherently rational basis. It gives the designer an excellent opportunity to assess topology change options on the basis of his evaluation of design trade-offs in terms of implementation cost, benefit in reduced additional area requirement, increased heat recovery, and possible impacts on safety and operability and so on. This selection procedure can be automated, without losing user control over the design process.

New Approach

The discussion so far has provided new insights into the nature of the HEN retrofit problem. In particular, the concept of the network pinch can be used to provide guidance for selecting topology changes, which forms the basis of the new retrofit approach. The new retrofit procedure consists of three stages: namely a diagnosis stage, an evaluation stage, and an optimization stage, as shown in Figure 3.

The diagnosis stage is designed to identify promising options for modifications, which include the relocation of existing exchangers, addition of new exchangers, and stream splitting. The stream split is determined using the heuristic by Asante and Zhu (1997). There are two linear models used

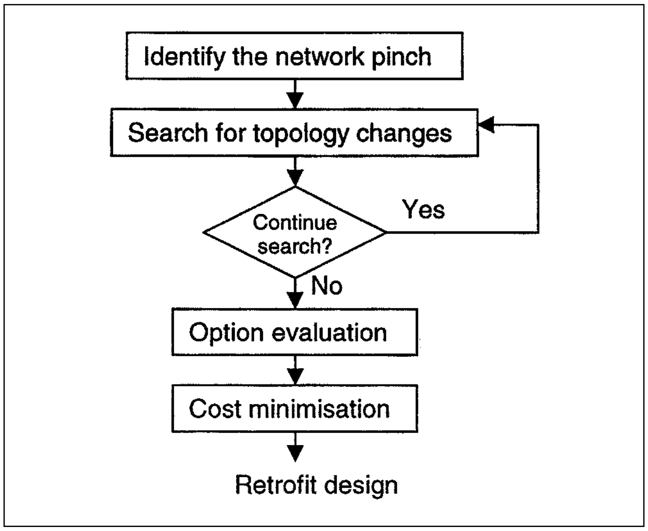

Figure 3. Procedure of the new approach.

in the diagnosis stage. Although these linear models are similar in many aspects, they are significantly different from those currently published in the literature. The LP model (P1) is used for identification of the heat recovery limits in the existing network by pushing the network to its maximum heat recovery limit without altering the network topology. This process identifies the pinching matches and the network pinch, which initiates the search for topology changes. The MILP model P2 is then used repeatedly in a sequential manner to identify topology changes which are indicated by the network pinch rule as being capable of overcoming the network pinch. The new network pinch is determined at the same time when topology changes are found.

Those modification options identified in the diagnosis stage will be further assessed in the evaluation stage. This stage provides opportunities for meaningful user interaction. In this stage, the cost for topology changes identified are estimated (such as costs for piping, foundation, and area) and safety and operability issues can be considered based on the user's experience and knowledge. As a result, impractical options are screened out. After the diagnosis and the evaluation stages, only promising options are selected. Cost estimate is only required for these selected options, which become a much simpler task than what would be if the cost estimates for all possible modification options are required prior to design.

In the final stage of optimization, the options selected are optimized in terms of the trade-off between the capital invested and the heat recovery achieved. During this optimization, main structural features of a network remain same, except split structures are allowed to vary. In some cases, several different topologies can be obtained, and they are considered separately in the optimization stage.

The approach proposed involves a sequential selection of topology change options, because this provides significant and practical advantages over a pure simultaneous or more "black-box" optimization. The method can, however, be adapted for more simultaneous selection of topology change options, and the formulation of the mathematical models has taken this into account and provided this alternative.

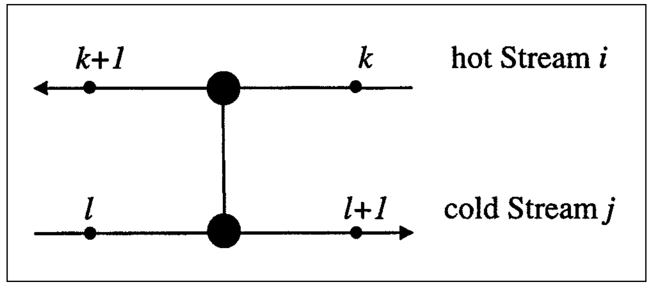

Figure 4. Definition of match *ijkl*.

Mathematical Formulations

To build the model, sets, parameters and variables are defined in the Notation section.

Network definition

Unlike many other mathematical models, the network definition used in this work does not involve enthalpy or temperature intervals; instead, location nodes of individual exchangers are defined on each stream in the network. As shown in Figure 4, a hot node k and a cold node l are assigned on each hot stream i and cold stream j, such that each exchanger match lies between two consecutive nodes. The location of an exchanger match $(ijkl)$ is thus defined by the node k on hot stream i and l on cold stream j at the exchanger inlet, and each of these nodes is associated with a temperature T_{ik} and T_{jl}, respectively. Similarly, process heaters (ujl) and coolers (uik) are defined by means of the nodes at which the heater or cooler is located, and the utility (u) used in the exchanger.

Basic Model for Identification of the Network Pinch (P1)

Objective function

The objective of this model is to determine the maximum heat recovery potential and meantime to identify the pinching matches in the HEN, which are two separate optimization tasks. These two tasks can be combined into a single objective function. In order to ensure that the maximization of heat recovery or the minimization of total heating duty takes a higher priority over the minimization of the number of pinching matches, two scaling constants c_1 and c_2 are used to ensure this priority

$$\text{Minimize } c_1 \sum_{ujl \in H} Q_{u,j,l} + c_2 \sum_{ijkl \in ME} p^1_{i,j,k,l} + c_2 \sum_{ijkl \in ME} p^2_{i,j,k,l} \quad (1)$$

where

$$c_1 \gg c_2$$

The variables p^1_{ijkl} and p^2_{ijkl} measure how close the temperature approaches at the hot and cold end, respectively, of the exchanger $(ijkl)$ are to the limiting driving force or the exchanger minimum approach temperature (EMAT). They are defined as continuous variables bounded between zero and one. When an exchanger is pinched at its hot or cold end, the corresponding p_{ijkl} variable takes a value of one, while, when the exchanger is not pinched, both variables have a value less than one (but greater than or equal to zero). The sum of these variables thus provides a measure of the number of pinched exchangers in the HEN. Minimizing the sum of these variable is, therefore, equivalent to minimizing the number of pinched exchangers, which can ensure that only those matches whose limiting temperature driving force cannot be relaxed by transferring heat in a loop are counted as pinching matches.

Match heat balances

Equation 2 provides the match heat balances for the hot and cold streams, respectively

$$T_{i,k+1} = T_{i,k} - \frac{1}{CP_i}\left[\sum_{j,l} Q_{ijkl \in ME} + \sum_{u} Q_{uik \in C}\right]$$

$$T_{j,l+1} = T_{j,l} + \frac{1}{CP_j}\left[\sum_{i,k} Q_{ijkl \in ME} + \sum_{u} Q_{ujl \in H}\right] \qquad (2)$$

The network temperatures $T_{i,k}$ and $T_{j,l}$ need to be bounded between the supply and target temperatures of their respective streams

$$\begin{aligned} TT_i \le T_{i,k} &\le TS_i, && 1 < k < N_i \\ T_{i,k} &= TS_i, && \text{for } k = 1 \\ T_{i,k} &= TT_i, && \text{for } k = N_i \\ TS_j \le T_{j,l} &\le TT_j, && 1 < l < N_j \\ T_{j,l} &= TS_j, && \text{for } l = 1 \\ T_{j,l} &= TT_j, && \text{for } l = N_j \end{aligned} \qquad (3)$$

It must be noted that the bounds on the temperatures of the first and last nodes of each stream ensures that the heating and cooling requirements of each stream is satisfied. In cases where some of the stream target temperatures are "soft" (that is, when some stream target temperatures can be allowed to vary slightly), then these bounds can be appropriately relaxed to account for this flexibility.

Match temperature approach constraints

Equations 4 and 5 define and constrain the hot and cold end temperature approaches of each heater, cooler, and process exchanger match to be greater than EMAT. The EMAT can be specified as any non-negative number, but a value which reflects the economics and practicalities of the network design is generally more appropriate.

$$\begin{aligned} DT^1_{ijkl \in ME} &= T_{i,k+1} - T_{j,l} \\ DT^2_{ijkl \in ME} &= T_{i,k} - T_{j,l+1} \\ DT_{uik \in C} &= T_{i,k+1} - T_{cu} \\ DT_{ujl \in H} &= T_{hu} - T_{j,l+1} \end{aligned} \qquad (4)$$

Utilities are defined as point utilities, and, as such, only the cold side of coolers and the hot side of the heaters need to be checked to ensure that temperature feasibility is maintained

$$\begin{aligned} DT^1_{ijkl \in ME} &\ge \text{EMAT} \\ DT^2_{ijkl \in ME} &\ge \text{EMAT} \\ DT_{uik \in C} &\ge \text{EMAT} \\ DT_{ujl \in H} &\ge \text{EMAT} \end{aligned} \qquad (5)$$

Identification of pinching matches

Two continuous variables p^1_{ijkl} and p^2_{ijkl} are defined for identification of the pinching matches

$$\begin{aligned} \left(1 - p^1_{ijkl}\right) &\le DT^1_{ijkl} - \text{EMAT} \quad ijkl \in ME \\ \left(1 - p^2_{ijkl}\right) &\le DT^2_{ijkl} - \text{EMAT} \quad ijkl \in ME \end{aligned} \qquad (6)$$

where

$$0 \le p^1_{ijkl} \le 1 \text{ and } 0 \le p^2_{ijkl} \le 1$$

Since the p_{ijkl} variables are minimized in the objective function, they always tend to move towards their lower bound. This means that, for exchangers which are not pinched, the value of the corresponding p_{ijkl} will be zero. For exchangers whose DT is less than one degree larger than the EMAT, however, the value of the corresponding p_{ijkl} variable will be equal to the difference between the DT and EMAT.

To explicitly count the number of pinching matches, it would have been necessary to define the p_{ijkl} variables as binary variables. As, however, the exact number of pinching matches is not required, the p_{ijkl} variables are defined as continuous variables (bounded between zero and one). The basic HEN model thus remains as a simple linear programming (LP) model.

Model for Topological Changes (P2)

Objective function

The objective function defined in Eq. 1 for the basic model is modified to include a measure of any pinching matches created by the insertion of the new exchanger, relocation of existing exchangers, and utility modifications. The utility modifications include the addition of new utility exchangers (such as steam generation by process streams), switch of steam levels (such as change current use of high pressure to low pressure steam), and change to the heat loads of existing utility exchangers. Since multiutility is considered, the objective then becomes to minimize the overall utility cost while identifying the network pinch. With this objective, heat recovery is maximized in order to save more expensive utilities

$$\text{minimize } c_1\left[\sum_{ujl\in H} CH_u Q_{ujl} + \sum_{uik\in C} CC_u Q_{uik} + \sum_{ujl\in NH} CH_u Q_{ujl} + \sum_{uik\in NC} CC_u Q_{uik}\right] + c_2 \sum_{ijkl\in ME\cup NE\cup RE\cup NH\cup NC} p^1_{i,j,k,l} + c_2 \sum_{ijkl\in ME\cup NE\cup RE\cup NH\cup NC} p^2_{i,j,k,l}$$

where

$$c_1 \gg c_2 \tag{7}$$

Match heat balances

The match heat balance equations are similar to those of the basic heat exchanger model. They, however, include additional terms to account for possible topological change options. To allow for the possibility of inserting a new exchanger (or moving an existing one) to a location between two existing exchangers, a new mode is created. All the exchangers that could potentially be located in this position share this node, as only one of them will eventually be placed.

$$T_{i,k+1} = T_{i,k} - \frac{1}{CP_i}\left[\sum_{j,l} Q_{ijkl\in ME} + \sum_{j,l} Q_{ijkl\in NE} + \sum_{j,l} Q_{ijkl\in RE} + \sum_{u} Q_{uik\in C} + \sum_{u} Q_{uik\in NC}\right]$$
$$T_{j,l+1} = T_{j,l} + \frac{1}{CP_j}\left[\sum_{i,k} Q_{ijkl\in ME} + \sum_{i,k} Q_{ijkl\in NE} + \sum_{i,k} Q_{ijkl\in RE} + \sum_{u} Q_{ujl\in H} + \sum_{u} Q_{ujl\in NH}\right] \tag{8}$$

As in the basic model, the network temperatures must be bounded between the stream supply and target temperatures. These bounds are defined in Eq. 3.

Topological change control

New Process-Process Match Placement Control. Two aspects of new matches need to be controlled. First, when the match is not placed, the match heat load must be forced to zero, and, secondly, the number of modifications allowed may need to be specified. This is done by introducing a binary variable $z_{ijkl\in NE}$, which takes the value one when the exchanger is placed, and zero when the exchanger is not placed

$$Q_{ijkl\in NE} \le \Delta H_i z_{ijkl\in NE}$$
$$\sum_{ijkl\in NE} z_{ijkl} \le \text{MODS1} \tag{9}$$

Exchanger Relocation Control. Similar to the addition of new process-process exchanger, $z_{ijkl\in RE}$ is introduced for the case of relocation to ensure that when an existing match is relocated, its binary variable $z_{ijkl\in RE}$ takes the value one and otherwise it becomes zero. In the case of relocation, however, the corresponding existing match must be simultaneously removed from the HEN when the match is relocated to a new position. It must be noted that each relocated exchanger retains one node in common with the exchanger whose place it is taking, because only one side of an exchanger (that is, either the hot stream side or the cold stream side) is relocated. This feature is used to control the relocation of exchangers in Eq. 10

$$Q_{ijkl\in ME} \le \Delta H_i\left(1 - \sum_{jl} z_{ijkl\in RE}\right)$$
$$Q_{ijkl\in ME} \le \Delta H_i\left(1 - \sum_{ik} z_{ijkl\in RE}\right)$$
$$\sum_{ijkl\in RE} z_{ijkl} \le \text{MODS2} \tag{10}$$

Utility Switch Option Control. In the case of a utility switch, when an alternative utility is selected (for example, $z_{ujl\in SH|u\in V} = 1$), the current utility load is set to be zero ($Q_{ujl\in H|u\in U} = 0$)

$$Q_{uik\in C|u\in U} \le \Delta H_i\left(1 - \sum_{v\in V, v\ne u} z_{vik\in SC}\right)$$
$$Q_{ujl\in H|u\in U} \le \Delta H_j\left(1 - \sum_{v\in V, v\ne u} z_{ujl\in SH}\right)$$
$$\sum_{uik\in SC} z_{uik} \le \text{MODS3}$$
$$\sum_{ujl\in SH} z_{ujl} \le \text{MODS4} \tag{11}$$

New Utility Exchanger Placement Control. Two binary variables $z_{ujl\in NH}$ and $z_{uik\in NC}$ are introduced to control the placement of new hot and cold utility matches, respectively. These variables take the value one when a corresponding utility exchanger is placed, and zero when it is not placed

$$Q_{ujl\in NH} \le \Delta H_j z_{ujl\in NH}$$
$$Q_{uik\in NC} \le \Delta H_i z_{uik\in NC}$$
$$\sum_{ujl\in NH} z_{ujl} \le \text{MODS5}$$
$$\sum_{uik\in NC} z_{uik} \le \text{MODS6} \tag{12}$$

Overall Control of the Number of Modifications.

$$\sum_{uik\in NC} z_{uik} + \sum_{ujl\in NH} z_{ujl} + \sum_{ijkl\in NE} z_{ijkl} + \sum_{ijkl\in RE} z_{ijkl} + \sum_{ujl\in SH} z_{ujl} + \sum_{uik\in SC} z_{uik} \le \text{MOD7} \tag{13}$$

Match temperature approach constraints

Equations 4 and 5 defined in P1 are used in this model as well, but, in addition, the temperature approaches of topological change options need to be defined and bounded above EMAT.

For New Exchangers and Relocation.

$$\begin{aligned} DT^1_{ijkl\in NE\cup RE} &= T_{i,k+1} - T_{j,l} + c_3(1 - z_{ijkl\in NE\cup RE}) \\ DT^2_{ijkl\in NE\cup RE} &= T_{i,k} - T_{j,l+1} + c_3(1 - z_{ijkl\in NE\cup RE}) \\ DT^1_{ijkl\in NE\cup RE} &\geq \text{EMAT} \\ DT^2_{ijkl\in NE\cup RE} &\geq \text{EMAT} \end{aligned} \tag{14}$$

For New Utility Exchangers and Steam Level Switch.

$$\begin{aligned} DT_{ijl\in NH\cup SH} &= T_{hu} - T_{j,l} + c_3(1 - z_{ujl\in NH\cup SH}) \\ DT_{uik\in NC\cup SC} &= T_{i,k} - T_{cu} + c_3(1 - z_{uik\in NC\cup SC}) \\ DT_{ujl\in NH\cup SH} &\geq \text{EMAT} \\ DT_{uik\in NC\cup SC} &\geq \text{EMAT} \end{aligned} \tag{15}$$

These bounds are only relevant when a topological change is made, and for this reason, the constant c_3 is used to deactivate the bounds when the exchanger is not placed. The constant c_3 is assigned a large value (at least EMAT). Consequently, when a topological change is not made (that is, when the binary variable is set to zero), the temperature approach DT will be assigned a value which is always greater than EMAT. When the match is placed (that is, when the binary variable is set to one), DT denotes the actual temperature approach, thus ''activating'' the match temperature constraints.

Identification of pinching matches

For New Exchanger and Relocation.

$$\begin{aligned} (1 - p^1_{ijkl}) &\leq DT^1_{ijkl} - \text{EMAT} \qquad ijkl \in NE \cup RE \\ (1 - p^2_{ijkl}) &\leq DT^2_{ijkl} - \text{EMAT} \qquad ijkl \in NE \cup RE \end{aligned} \tag{16}$$

where

$$0 \leq p^1_{ijkl} \leq 1 \text{ and } 0 \leq p^2_{ijkl} \leq 1$$

For New Utility Exchanger and Steam Level Switch.

$$\begin{aligned} (1 - p_{ujl}) &\leq DT_{ujl} - \text{EMAT} \qquad ujl \in NH \cup SH \\ (1 - p_{uik}) &\leq DT_{uik} - \text{EMAT} \qquad uik \in NC \cup SC \end{aligned} \tag{17}$$

where

$$0 \leq p_{uik} \leq 1, \qquad 0 \leq p_{ujl} \leq 1$$

Remarks

(a) About the Network Pinch Concept. The network pinch plays a significant role in simplifying the MILP model P2 by removing those options which would not enable the transfer of heat from below to above the network pinch. This thinning out of the possible options can be performed automatically during the optimization process, once the location of the network pinch of the current HEN has been established. In this way, only potentially beneficial options are taken into account, and the size of the resulting model P2, particularly the number of binary variables, is considerably smaller than would be the case without the thinning out guided by the network pinch rules.

(b) About Utility Modifications. The model P2 can also deal with situations where modification of the existing utility system is desirable, or when such modifications define the retrofit objective. In most cases individual processes are serviced by a central utility system, and any modification to the utility system has a significant effect on the other processes and consequently on the optimality of the site as a whole. For this reason, the optimization of the utility system must generally be considered over a whole operating site. A technique for site wide utility optimization has been developed (Makwana et al., 1998), which identifies utilities that are worth saving and generating. By using the model P2, the modifications associated with reduction of utility usage, steam level switching, and/or addition of new utility exchangers can be readily identified.

(c) Sequential Search and Simultaneous Search. Although the model P2 is designed for selecting topology change options in a sequential manner, it can also be used for the simultaneous selection of more than one topology change at each stage. When a sequential search strategy is employed, options for relocation, new addition, and stream splitting are exploited separately. This is done by manipulating control equations defined previously. When one type of option is considered at one stage, the other type of options can be removed from consideration by setting the corresponding binary variables to be zero. Also, the number of modifications sought at one stage can be defined by setting a value to the parameter MOD in the corresponding control equation. In this case, the order of search for options should be specified. It is suggested to start the search for relocation options first, and then search for new exchanger options. Stream splitting options are only considered when indicated by the heuristic (Asante and Zhu, 1997). The user can, of course, modify this strategy by having a different order of running the models.

On the other hand, by increasing the MOD parameters, the search process can be carried out more simultaneously. Due to the limitations inherent in a ''best first search'' approach, however, it is recommended that alternative search paths be investigated to find several competing designs. This provides additional confidence for the design obtained.

Extending the Models for Segmented Streams

Stream segment model

In this work, each segmented stream is modeled by a main stream and several substreams. The main stream and each of the substreams have identical nodes; thus, all exchangers located on the segmented stream have a position on the main

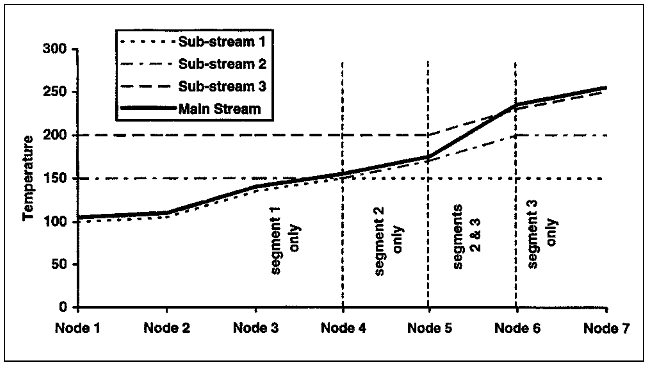

Figure 5. Stream segment model.

stream and each of the substreams. The main stream spans the whole temperature range of the segmented streams, while each of the substreams only spans the temperature range of the particular stream segment which it represents.

The stream segment model for a three segment stream with supply and target temperatures of 100°C and 250°C, respectively, is illustrated in Figure 5. The three segments which make up this stream have supply and target temperatures of 100°C and 150°C, 150°C and 200°C, and 200°C and 250°C. This illustration demonstrates how all possible match placement combinations can be accounted for by this model.

As can be seen, between nodes 1 and 4, the temperature profile of the main stream exactly matches that of substream 1, and this means that the heat capacity flow rate of the main stream between these nodes is equal to the heat capacity flow rate of segment 1. It may be noted that the slope of the main stream temperature profile is not constant in this region, but as the abscissa of this plot is not enthalpy, the slope of the profile has no relation with the stream heat capacity flow rate.

The figure, therefore, shows that the first three exchangers, between node pairs [1,2], [2,3] and [3,4], are all located fully on segment 1. These exchangers satisfy all the heat-transfer requirement of segment 1.

Between nodes 4 and 5, the main stream temperature profile follows that of substream 2, and this means that the exchanger between node pairs (4,5) is located fully on this substream. As the substream does not attain its target temperature, this exchanger does not fully satisfy the heat transfer needs of the substream. Between nodes 5 and 6, the main stream temperature profile lies between that of substreams 2 and 3; this shows that the exchanger between node pairs (5,6) spans two segments and lies at the end of segment 2 and at the beginning of segment 3. This exchanger completes the heat transfer required by segment 2.

Finally, between nodes 6 and 7, the temperature profile of the main stream follows that of substream 3, and this means that the exchanger between node pairs (6,7) is located fully on segment 3. This final exchanger satisfies the last substream's need for heat transfer, and completes the heat transfer of the main stream.

The essential feature of this model is that the heat-transfer requirements of ''earlier'' substreams must be satisfied first. In other words, until the first substream attains its target temperature, the second substream must remain at its supply temperature, and until the second substream attains its target temperature, the third substream must remain at its supply temperature and so on. This requirement can be formulated mathematically by combining the creative use of binary variables with appropriately defined bounds for all the substream temperatures.

Heat balances

The heat balance equations need to be modified to take into account the presence of segmented streams, but all the other equations remain unchanged. In addition to this, further constraints are required to fully model the substreams.

Each segmented hot stream is modeled as main stream i and its constituent substreams m. In order to emphasize the link between the substreams and the main stream to which they belong, each hot substream is denoted as i_m. Similarly, each cold substream is denoted as j_n. Equation 18 provides the heat balance for segmented streams

$$T_{i,k+1} = T_{i,k} - \left[\sum_{j,l,m} \frac{q_{i_m jkl \in ME}}{cp_{i_m}} + \sum_{m,u} \frac{q_{ui_m k \in C}}{cp_{i_m}} + \sum_{j,l,m} \frac{q_{i_m jkl \in NE}}{cp_{i_m}} + \sum_{j,l,m} \frac{q_{i_m jkl \in RE}}{cp_{i_m}} + \sum_{m,u} \frac{q_{ui_m k \in NC}}{cp_{i_m}} \right]$$

$$T_{j,l+1} = T_{j,l} + \left[\sum_{i,k,n} \frac{q_{ij_n kl \in ME}}{cp_{j_n}} + \sum_{n,u} \frac{q_{uj_n l \in H}}{cp_{j_n}} + \sum_{i,k,n} \frac{q_{ij_n kl \in NE}}{cp_{j_n}} + \sum_{i,k,n} \frac{q_{ij_n kl \in RE}}{cp_{j_n}} + \sum_{n,u} \frac{q_{uj_n l \in NH}}{cp_{j_n}} \right] \quad (18)$$

The main stream temperatures of segmented streams are also subject to their bounds defined previously. In addition, the following equations provide the link between the substream heat loads ($q_{i_m jkl}$ or $q_{ij_n kl}$) and the match heat load Q_{ijkl}. These equations ensure that the heat load of any exchanger on a segmented stream is equal to the sum of its constituent substream heat loads

$$Q_{ijkl} = \sum_m q_{i_m jkl} = \sum_n q_{ij_n kl} \qquad ijkl \in ME \cup NE \cup RE$$

$$Q_{uik} = \sum_m q_{ui_m k} \qquad uik \in C \cup NC$$

$$Q_{ujl} = \sum_n q_{uj_n l} \qquad ujl \in H \cup NH \quad (19)$$

The following equations define the individual substream heat balances, and relate the substream heat loads with the appropriate substream temperatures $t_{i_m,k}$ and $t_{j_n,l}$.

$$t_{i_m,k+1} = t_{i_m,k} - \frac{1}{cp_{i_m}} \left[\sum_{j,l} q_{i_m jkl \in ME} + \sum_u q_{ui_m k \in C} + \sum_{j,l} q_{i_m jkl \in NE} + \sum_{j,l} q_{i_m jkl \in RE} + \sum_u q_{ui_m k \in NC} \right]$$

$$t_{j_n,l+1} = t_{j_n,l} + \frac{1}{cp_{j_n}} \left[\sum_{i,k} q_{ij_n kl \in ME} + \sum_u q_{uj_n l \in H} + \sum_{i,k} q_{ij_n kl \in NE} + \sum_{i,k} q_{ij_n kl \in RE} + \sum_u q_{uj_n l \in NH} \right] \quad (20)$$

These substream temperatures must also be bounded between their own supply and target temperatures (ts and tt)

$$
\begin{aligned}
tt_{i_m} \le t_{i_m,k} \le ts_{i_m} &\qquad 1 < k < N_{i_m}\\
t_{i_m,k} = ts_{i_m} &\qquad k = 1\\
t_{i_m,k} = tt_{i_m} &\qquad k = N_{i_m}\\
ts_{j_n} \le t_{j_n,l} \le tt_{j_n} &\qquad 1 < l < N_{j_n}\\
t_{j_n,l} = ts_{j_n} &\qquad l = 1\\
t_{j_n,l} = tt_{j_n} &\qquad l = N_{j_n}
\end{aligned} \tag{21}
$$

Logical constraints

As discussed previously, for the stream segment model to work correctly, the heat-transfer requirements of earlier segments must always be satisfied first. This requirement can be expressed logically as:

IF substream m has not attained its target temperature,

THEN substream m + 1 must remain at its supply temperature.

This logical relationship is implemented using the binary variables $x_{i_m,k}$ and $x_{j_n,l}$ in the following equations. It must be noted that due to the definition of the bounds defined in Eqs. 22, the values of the expressions on the righthand side of the first and third equations and the values on the lefthand side of the second and fourth equations will always lie between zero and one

$$
\begin{aligned}
x_{i_m,k} &\le \frac{ts_{i_m} - t_{i_m,k}}{ts_{i_m} - tt_{i_m}}\\
\frac{ts_{i_{m+1}} - t_{i_{m+1},k}}{ts_{i_{m+1}} - tt_{i_{m+1}}} &\le x_{i_m,k}\\
x_{j_n,l} &\le \frac{ts_{j_n} - t_{j_n,l}}{ts_{j_n} - tt_{j_n}}\\
\frac{ts_{j_{n+1}} - t_{j_{n+1},l}}{ts_{j_{n+1}} - tt_{j_{n+1}}} &\le x_{j_n,l}
\end{aligned} \tag{22}
$$

The effect of these equations can be illustrated as follows for a segmented hot stream i. For any node k at which the substream m has not attained its target temperature (that is, $t_{i_m,k} > tt_{i_m}$), the binary variable $x_{i_m,k}$ will be forced to a value of 0. This in turn forces the lefthand side of the second equation to a value of zero, which is equivalent to forcing the temperature of substream $m+1$ to remain at its supply temperature ($t_{i_{m+1},k} = ts_{i_{m+1}}$).

Thus, as long as substream m has not attained its target temperature, substream $m+1$ is forced to remain at its supply temperature, and this ensures that the heat-transfer requirements of "earlier" substreams are satisfied first. It follows from Eq. 20 that if the substream $m+1$ remains at its supply temperature at both nodes k and $k+1$ (that is, $t_{i_{m+1},k+1} = t_{i_{m+1},k} = ts_{i_{m+1}}$), then the heat load of any exchanger located at node k of the substream will be forced to zero. In other words, no exchangers are placed on substream $m+1$ until substream m is satisfied.

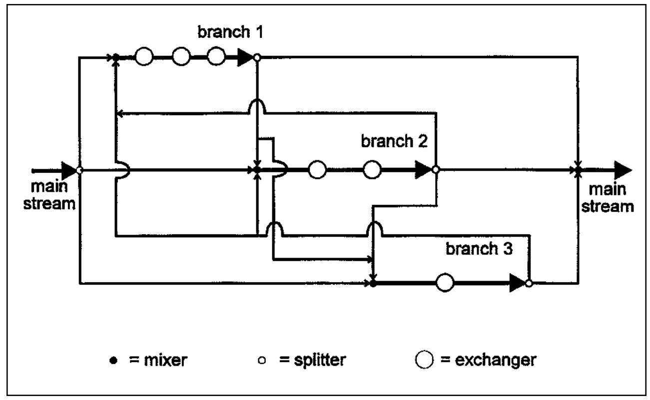

Figure 6. Stream split model.

Extending the Models to Handle Stream Splits

Stream split model

In many heat exchanger network designs, some of the process streams are split into two or more branches, each of which is matched with other streams before being mixed together to produce the original stream. These stream split configurations may vary in complexity from a simple two-branch stream split with one exchanger located on each branch, to complex multiple branch stream splits with bypass configurations.

All stream-split configurations contain an initial split of the stream into two or more branches and a final mixer in which the branches are recombined to reproduce the original stream. Some of the branches will have exchangers on them, while others may act as bypass streams and feature no exchangers at all. In some cases, one or more of the original branches may be split into a number of sub-branches which could in turn be mixed with other branches and sub-branches to produce other branches.

All these features can be represented using Figure 6, which is based on the superstructure of Floudas et al. (1986), who demonstrated that this superstructure could be used to represent any stream-split configuration by appropriately defining the split fractions of the main splitter and each of the branch splitters. The original model by Floudas et al. (1986) had only one exchanger located on each branch, but in this application each branch can have any number of exchangers on it. The detailed modeling discussions for the extension of Floudas et al.'s superstructure can be found from Asante (1996).

Mathematical Formulation for Optimization Stage

A set of topological change options are determined from the diagnosis stage and assessed further in the evaluation stage. As a result, these topological changes selected are technically feasible and economically beneficial. During the final stage of optimization, these options are optimized simultaneously in terms of the trade-off between the capital invested and the heat recovery achieved. Apart from exchangers involved in stream split configurations, none of the exchangers in the HEN is relocated during the optimization. A small superstructure (Asante et al., 1996) is used to optimize the series/parallel arrangement of exchangers involved in stream split configurations, and the flow fractions of each of the split branches. This superstructure is termed as "small," because it is only defined for exchangers involved in stream split configurations. During the optimization, both the heat loads of exchangers and the stream split configurations are optimized.

It should be noted that in the model formulation for the final stage of optimization, the network definition (node representation) and some of the notations are the same as that used in the diagnosis stage. Additional notations are given separately in the Notation section.

Objective function

The objective function is defined in terms of cost minimization including costs for utilities and additional area. As the topology of the networks is normally fixed at this stage, the implementation costs are constant and could be omitted from consideration

$$\min imize \sum_{e \in HE} CH_e Q_e + \sum_{e \in CE} CC_e Q_e + R \sum_{e \in E} b_e \left(A_e^a \right)^{c_e} \tag{23}$$

When heat recovery level is fixed, this objective function reduces to minimization of capital cost.

Match heat balances

The heat balance is conducted on a match basis, rather than on a stream basis as in the case of previous models.

$$CP_i (T_{i,k} - T_{i,k+1}) = CP_j (T_{j,i+1} - T_{j,l}) \quad ijkl \in E \quad (24)$$

The exchanger heat loads are defined using the hot stream enthalpy change for process exchangers and coolers, and the cold stream enthalpy change for process heaters

$$Q_{e \in PE} = CP_i (T_{i,k} - T_{i,k+1})$$
$$Q_{e \in CE} = CP_i (T_{i,k} - T_{i,k+1})$$
$$Q_{e \in NE} = CP_j (T_{j,l+1} - T_{j,l}) \quad (25)$$

The network temperatures $T_{i,k}$ and $T_{j,l}$ need to be bounded between the supply and target temperatures of their respective streams. Equation 3 can be used to achieve this purpose.

Match temperature approach constraints

Equation 26 defines and constrains the match temperature approaches at the hot and cold ends of every match

$$DT^1_{e \in PE} = T_{i,k+1} - T_{j,l}; \qquad DT^2_{e \in PE} = T_{i,k} - T_{j,l+1}$$
$$DT^1_{e \in CE} = T_{i,k+1} - T_{cu}; \qquad DT^2_{e \in CE} = T_{i,k} - T_{cu}$$
$$DT^1_{e \in HE} = T_{hu} - T_{j,l}; \qquad DT^2_{e \in HE} - T_{hu} = T_{j,l+1}$$
$$DT^1_{e \in PE} \geq \text{EMAT}; \qquad DT^2_{e \in PE} \geq \text{EMAT}$$
$$DT^1_{e \in CE} \geq \text{EMAT}; \qquad DT^2_{e \in CE} \geq \text{EMAT}$$
$$DT^1_{e \in HE} \geq \text{EMAT}; \qquad DT^2_{e \in HE} \geq \text{EMAT} \quad (26)$$

The Paterson (1978) approximation is used to estimate the exchanger logarithmic mean temperature approach difference, and this yields Eq. 27 for all the network exchangers

$$DTLM_e = 2/3 \sqrt{DT_e^1 DT_e^2} + 1/6 \left(DT_e^1 + DT_e^2 \right) \quad \forall e \in E \quad (27)$$

Match area calculation

The surface area of each process exchanger, heater and cooler is then defined by the following equation

$$A_e = Q_e / (U_e DTLM_e) \qquad \forall e \in E \tag{28}$$

In order to determine the additional area required by each exchanger, the slack variable S_e is defined as shown in Eq. 29 and bounded between zero and the installed area of the existing exchanger. The effect of these equations is that whenever the heat-transfer area (A_e) of an exchanger is less than the installed area (A_e^{exist}) of the exchanger, the slack variable S_e takes the value of A_e, thus forcing the values of A_e^a (additional area) to zero. When, however, the variable A_e exceeds A_e^{exist}, S_e takes its maximum value A_e^{exist}, and thus A_e^a defines the additional area required by the exchanger

$$S_e - A_e \leq 0$$
$$A_e^a - A_e + S_e = 0 \qquad \forall e \in E \tag{29}$$

where

$$0 \leq S_e \leq A_e^{\text{exist}}$$

It should be noted that the above model has been extended to deal with segmented streams and stream split configurations. This is done in a similar way as described previously.

Case Studies

The retrofit procedure has been implemented in GAMS (Brooke et al., 1992), and tested on several retrofit HEN design problems. Two case studies are used to illustrate the strength and versatility of the retrofit procedure.

Debottlenecking case study

This example was first introduced by Ahmad et al. (1989) and later used by Shokoya and Kotjabasakis (1991) to demonstrate the area matrix technique. The retrofit objective in this example is to debottleneck the HEN to cope with a 10% increase in crude throughput, and the main retrofit design constraint is the specification of a maximum furnace duty of 100 MW.

Figure 7 shows the grid diagram for the existing HEN. It must also be mentioned that some streams have been segmented linearly to account for the significant changes in the specific heat capacities of these streams with temperature.

Both previous designs (Ahmad et al., 1989; Shokoya and Kotjabasakis, 1991) are reported at a furnace duty of 99.6 MW, and, for purposes of comparison, this furnace duty was used for the targeted heat recovery. The minimum tempera-

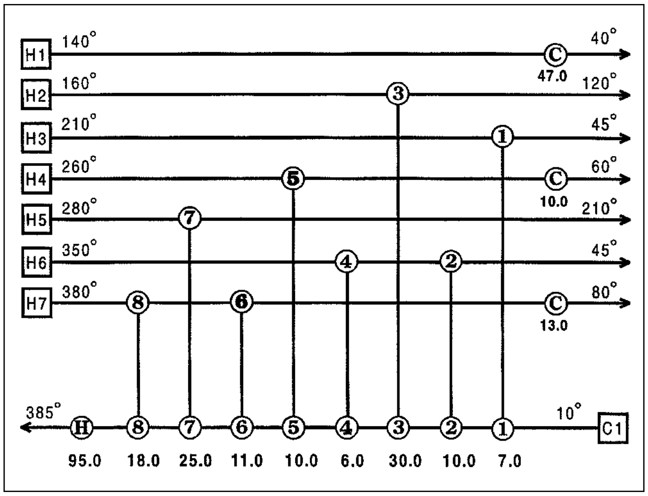

Figure 7. Original HEN before debottlenecking.

ture approach permitted in the HEN was set at 10°C. The following results are produced using the default procedure.

As a first step, the limits of the original HEN topology are established, and this is shown in Figure 8. The furnace duty at the maximum recovery ($R_{\max}$) for the given topology is 102.5 MW, and, as this is above the maximum allowable value of 100 MW, it implies that topology changes will be required in the retrofit design. Exchangers 5 and 6 are pinched at the $R_{\max}$.

The first modification option considered is exchanger resequence, and the option selected by the procedure is the resequence of Exchanger 4 as illustrated in Figure 9. This produces a 4.4 MW increase in heat recovery potential, and reduces the minimum furnace duty to 98.1 MW. Although

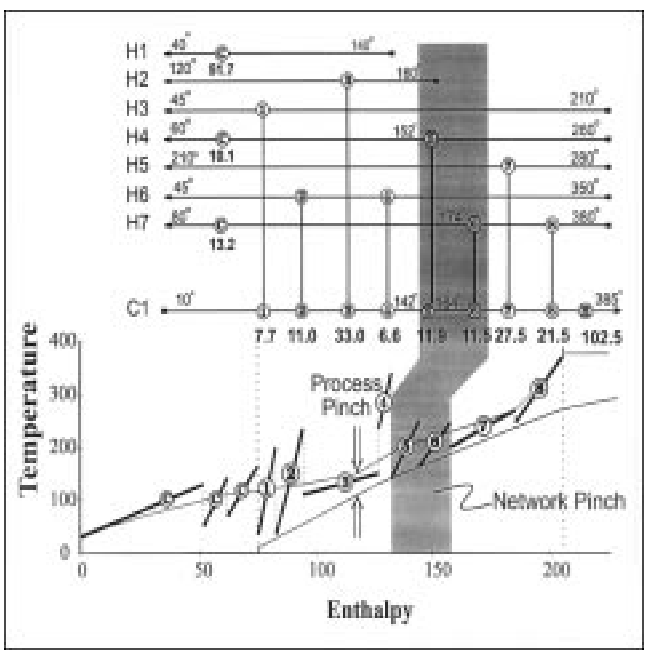

Figure 8. Limits of the original HEN in case study 1.

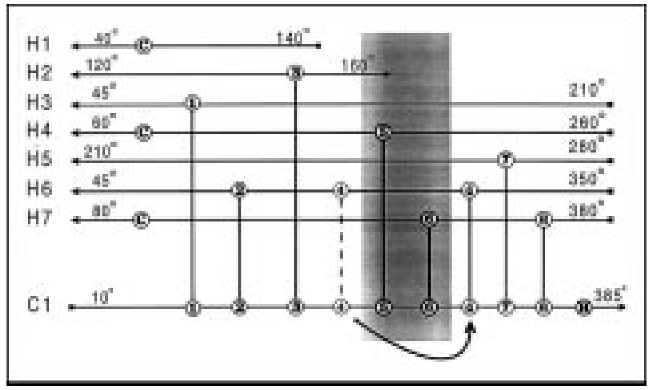

Figure 9. Resequence of exchanger 4: min $Q_H = 98.08$, $\Delta Q_{\text{REC}} = 4.4$.

the minimum furnace duty after this resequence is less than the objective of 99.6 MW, it is quite close to it. It can be predicted that design at or close to the topology $R_{\max}$ would generally require the use of excessive exchanger area. Thus, another topology change is sought to further increase the $R_{\max}$ and, consequently, reduce the exchanger area required in the HEN.

The topology produced after the resequence of Exchanger 4 features three adjacent pinching matches (Exchangers 4, 5 and 6), as shown in Figure 10. As the first of these pinching matches lies at the process pinch, the process and network pinches have become coincident, and this fulfils the conditions of the stream split heuristic. The search for resequence options is thus interrupted and the stream split is implemented.

Exchangers 4, 5 and 6 being the three adjacent pinching matches are placed in parallel with each other to produce a 1.8 MW increase in $R_{\max}$. Although the three exchangers are initially placed in parallel with each other (Figure 11), the final split configuration is determined during the following optimization stage.

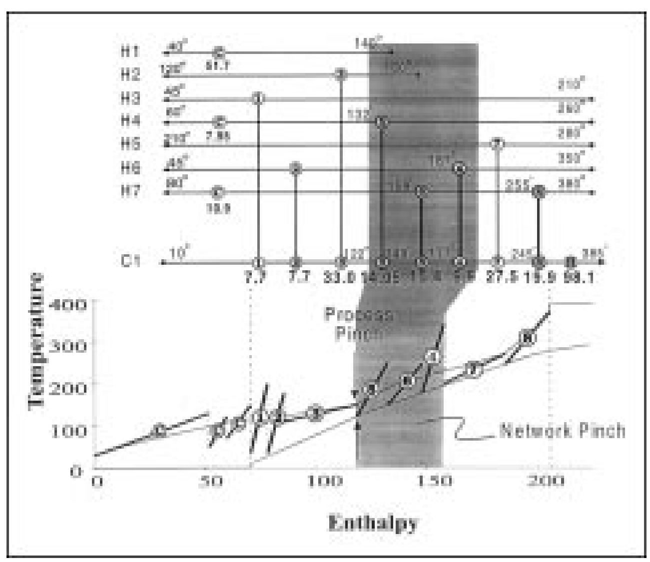

Figure 10. Limits in HEN after resequence.

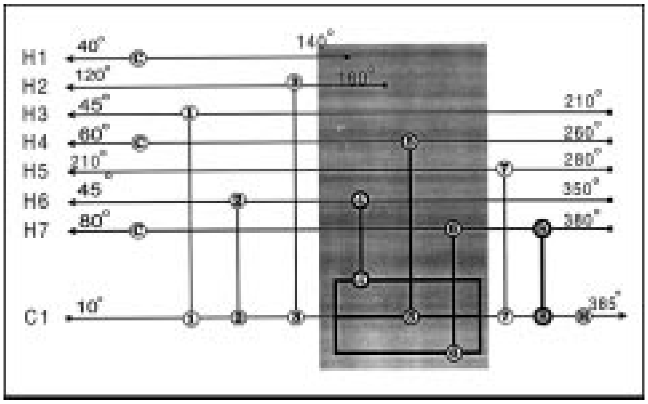

Figure 11. Stream split implementation: min $Q_H = 96.30$, $\Delta Q_{REC} = 1.8$.

The search for modifications could be stopped at this point, and the resulting topology is submitted to the optimization stage. If, however, the search is continued for another step, the next modification selected is the addition of a new exchanger. This further increases the R_{max} by 3.9 MW to give a minimum furnace duty of 92.4 MW. It is not possible at this stage to determine whether the addition of the new exchanger can be economically justified. The optimization stage will provide the necessary clarification.

After optimization at a fixed furnace duty of 99.6 MW, the retrofit design without the new exchanger required 1,974 m^2 of additional exchanger area, while the design with the new exchanger required only 1,265 m^2 (Figure 12). With this information, the two design options can be effectively compared to identify the ''best'' retrofit design. The installation cost of the new exchanger can be fairly accurately estimated at this stage to assist in the decision process, which is much simpler than initiating the design process by making such estimates for all new exchanger options.

A close look at the exchanger area requirements of each topology for a furnace duty of 99.6 MW reveals that the topology modifications selected by the proposed method con-

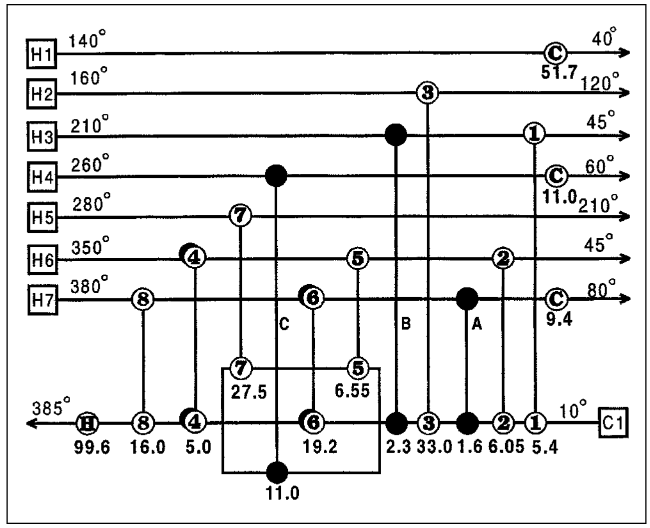

Figure 13. Retrofit design by Ahmad et al. (1989).

sistently reduce the exchanger area requirement of the HEN. This proves that although the objective function in the diagnosis stage does not explicitly consider area requirement, it nonetheless selects topology changes which reduce exchanger area requirement.

The design produced by using the proposed method (Figure 12) is compared well with the designs produced by Ahmad et al. (1989) and Shokoya and Kotjabasakis (1991), which are shown in Figures 13 and 14, respectively. The comparison is given in Table 1, which reveals that the new method requires the least number of modifications to the HEN, and requires exchanger area close to minimum.

Energy Retrofit Case Study

This case study was studied by Carlsson et al. (1993). The case study involves the retrofit of the heat exchanger network within a pulp and paper mill, so as to reduce the energy con-

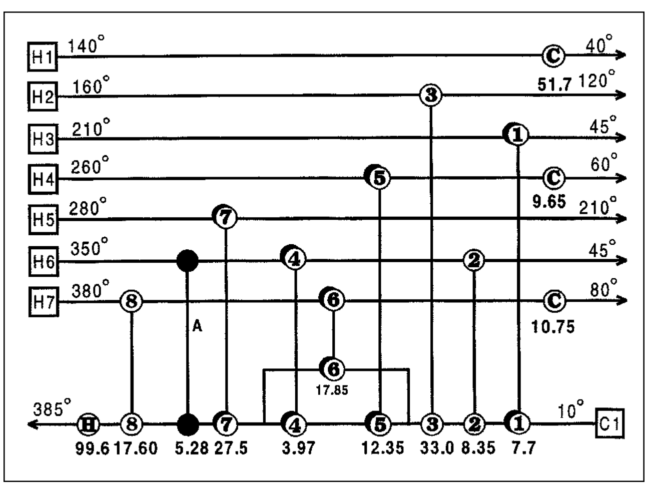

Figure 12. Retrofit design using the present method.

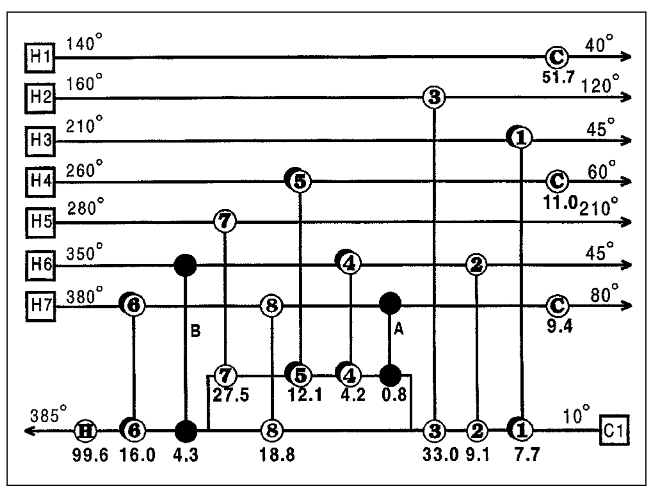

Figure 14. Retrofit design by Shokoya and Kotjabasakis (1991).

Table 1. Design Implications

	Ahmad et al. (1989) (Figure 13)	Shokoya and Kotjabasakis (1991) (Figure 14)	New Method (Figure 12)
New exchangers	3	2	1
Resequenced	1	2	1
Repiped	1	0	0
Stream splits	1 (1×3)	1 (1×2)	1 (1×2)
Existing (+area)	2	4	5
Additional area	1,990 m^2	1,257 m^2	1,265 m^2

sumed within the process, and the original network design is illustrated in Figure 15. The retrofit design by Carlsson et al. (1993) is shown in Figure 16, which is based on $\Delta T_{\min}$ of 18°C. The design produced by the present method for the same heat recovery level is given in Figure 17.

Table 2 shows a comparison between these two designs. It can be seen from this table that the Carlsson et al. (1993) design uses two more new exchangers than the design by the proposed method with only 14 m^2 less exchanger area. In terms of investment costs, the design by the proposed method has a cost of $139,000 which is about 20% less than the cost of the Carlsson et al. (1993) design. This demonstrates that the new approach consistently ensures that the network produced uses a minimum of topology changes with close to minimum area requirements.

Remarks

The new design procedure does not require a predefined heat recovery objective to initiate the design process. This is because it does not involve the decomposition of the design problem at the process pinch, nor the subdivision of the problem into temperature or energy intervals. This is particularly useful when the trade-off between total cost and heat recovery is uncertain.

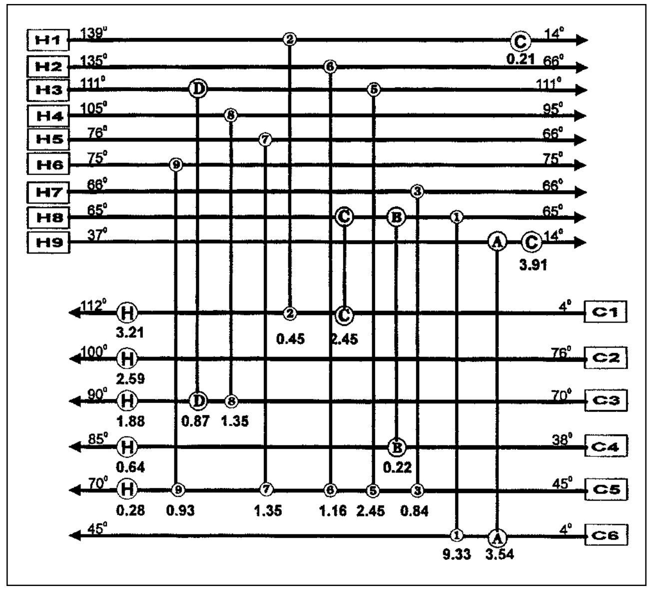

Figure 16. Retrofit design at global ΔT of 18°C (Carlsson et al., 1993).

It can be observed from the above two case studies that the major feature of the network pinch designs is their achievement of equivalent energy impact with fewer modifications, and only with marginally more area, comparing with existing methods. This can provide significant benefit for cases where modification costs (such as piping, foundation, and civil) are much more expansive than area costs, which is very common in industrial retrofit. However, if one wants to reduce additional area further, an additional modification could be implemented using Network Pinch method.

Note that the time required to generate these designs was very small. For example, the CPU time for the two cases was

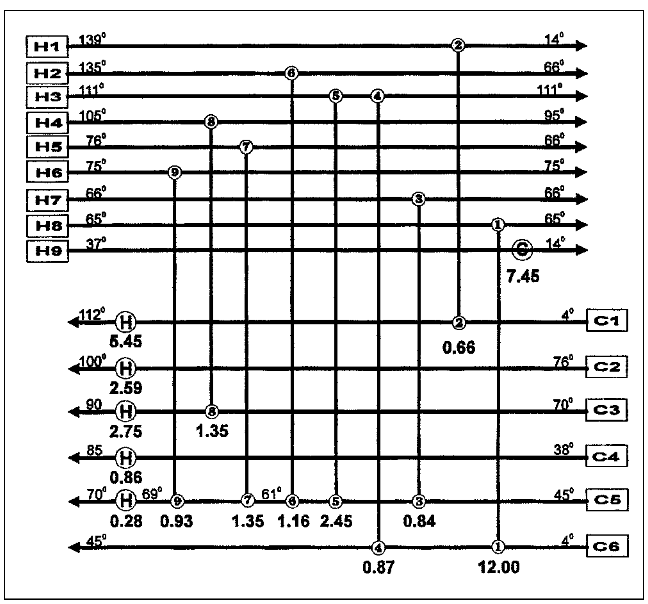

Figure 15. Original HEN design for case study 2.

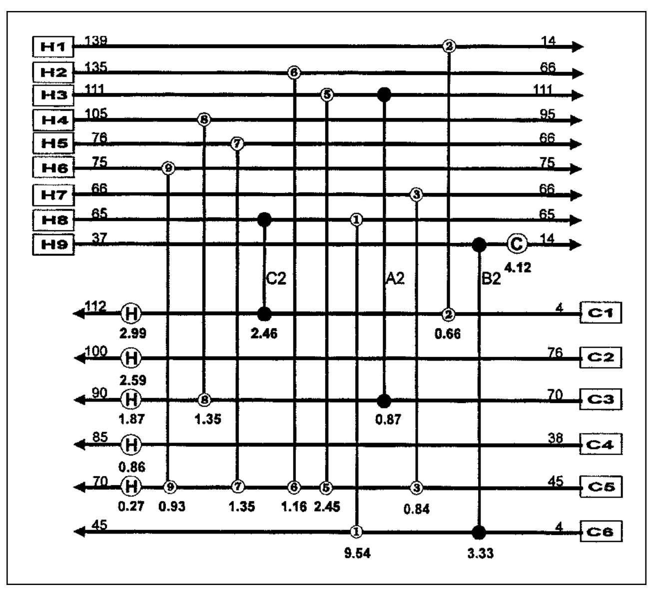

Figure 17. Retrofit design using the new method.

Table 2. Comparison of Two Designs

	Carlsson et al. (1993) (Figure 16)	New Design Method (Figure 17)
Additional area requirement	166 m^2	180 m^2
Number of new matches	5	3
Area cost	$58,000	$63,000
Fixed costs for new matches	$118,000	$76,000
Total Cost	$176,000	$139,000

35 s (7 MILP runs) and 20 s (5 MILP runs), respectively, using a 90 MHz OPUS Pentium PC. The rapidity with which the model generates solutions clearly makes it possible for several design options to be investigated for a given case study within a short time. This is a major advantage of the new approach.

Conclusions

This article introduces a completely new decomposition approach for the retrofit design of heat exchanger networks, which enables the automation of the design process without sacrificing user interaction. Essentially, this approach employs a two-stage decomposition, in which the first stage identifies a set of promising topology modifications, and the second stage optimizes the HEN resulting from the proposed modifications by trading off capital and energy costs.

Two mathematical models for the selection of topological modification options are presented. These models use the maximization of the HEN heat recovery potential as their optimization objective, and, as such, the nonlinear equations associated with the determination of the HEN area requirement are not required. This enables the models to be formulated as MILP models instead of MINLP models (which are difficult to solve), and ensures that the models can be solved efficiently on ordinary personal computers. Although the optimization objective used does not require the explicit determination of the exchanger area requirement, it ensures that the topology changes selected tend to minimize the additional area requirement of the HEN, while maximizing the potential for heat recovery in the HEN. This strength has been shown through the two case studies and other examples.

This article also introduces a new and versatile modeling representation for HEN (based on the definition of location nodes on each stream). This representation explicitly defines the topology of the HEN. Based on this representation, segmented streams can be modeled readily. The model can also be extended to handle HENs, which feature complicated stream split configurations and this demonstrates the versatility of the model.

The models are designed to identify one topology change option at a time, in a sequential fashion, and this ensures that the superstructure used at each stage remains small and manageable. In addition, this stepwise approach promotes user interaction during the design process. By changing the values of parameters (MODs), however, the models can be used to identify any number of topology changes simultaneously.

The retrofit procedure has been successfully tested on several industrial design problems including a refinery crude unit, which featured a complex bypass network structure of over 20 exchangers and 30 streams (many of which were segmented to account for variation in their heat capacity flow rates). The method has also been applied to case studies in the literature. The results obtained were comparable or superior to the previous best-known designs. From these case studies, it has been concluded that the procedure provides a truly effective method for HEN retrofit design.

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The financial support of BP International and the Process Integration Research Consortium (UMIST) in conducting this research is gratefully acknowledged.

Notation (Models P1 and P2)

Sets

$C = \{(uik) | uik$ is an existing cold utility match$\}$
$H = \{(ujl) | ujl$ is an exiting hot utility match$\}$
$I = \{i | i$ is a hot process stream$\}$
$J = \{j | j$ is a cold process stream$\}$
$K = \{k | k$ represents a node on a hot stream$\}$
$L = \{l | l$ represents a node on a cold stream$\}$
$M = \{m | m$ is a substream$\}$
$ME = \{(ijkl) | ijkl$ is an existing process match$\}$
$NE = \{(ijkl) | ijkl$ is a possible new exchanger match$\}$
$NC = \{(uik) | uik$ is a possible new cold utility match$\}$
$NH = \{(ujl) | ujl$ is a possible new hot utility match$\}$
$RE = \{(ijkl) | ijkl$ denotes an existing match possibly relocated$\}$
$SC = \{(uik) | uik$ denotes an existing cold utility match possibly switched$\}$
$SH = \{(ujl) | ujl$ denotes an existing hot utility match possibly switched$\}$
$U = \{u | u$ is a utility$\}$
$V = \{v | v$ is an alternative utility$\}$

Parameters

c_3 = a large value
CC = cost of a cold utility
CH = cost of a hot utility
CP = heat capacity flow rate
EMAT = exchanger minimum approach temperature
ΔH = enthalpy change for a stream
MOD = number of modification options
N = last node on a stream
TS = supply temperature for a main stream
TT = target temperature for a main stream
ts = supply temperature for a substream
tt = target temperature for a substream

Variables

DT^1 = approach temperature difference at the cold side of a match
DT^2 = approach temperature difference at the hot side of a match
DT = approach temperature difference for a utility match
p^1 = variable to measure pinching condition at the cold side of a match
p^2 = variable to measure pinching condition at the hot side of a match
p = variable to measure pinching condition for a utility match
Q = heat load of a match on main stream
q = heat load for a match on a substream
T = match temperature for main stream
t = match temperature for a substream
x = binary variable used to handle segmented streams
z = binary variable denoting existence or nonexistence of a match

Notation (NLP Model)

Sets

$E = \{e|e$ is a exchanger match$\}$
$HE = \{e|e$ is a hot utility exchanger match; $HE \subset E\}$
$CE = \{e|e$ is a cold utility exchanger match; $CE \subset E\}$
$PE = \{e|e$ is a process-process exchanger match; $PE \subset E\}$

Parameters

A^{exit} = area for existing exchangers
b = coefficient for exchanger cost
c = exponential coefficient for exchanger cost
R = annualized cost factor
U = overall heat-transfer coefficient
Γ = a large value

Variables

A = variable exchanger area
A^a = additional exchanger area
DTLM = logarithmic temperature difference
S = slack variable

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