CHAPTER 4

HEN DESIGN USING MATCH PATTERN APPROACH

There are two fundamentally different approaches for heat exchanger network synthesis, based on levels of problem description, - optimization and heuristics. In an optimization method, a HEN synthesis problem must be translated into an optimization model and the translated problem is solved by finding a set of variables that define a minimum value of a utility function. However, this method is limited by problem and design requirement translation. For the heuristic method, the domain-specific problem-solving knowledge must be available or developed. There have been few attempts to develop an automated (computer programmed) HEN design system by using a heuristic model.

Heuristic knowledge of heat exchanger network synthesis has been published in the literature for over two decades, but has not been systematically used. In this chapter, a number of match patterns, which were developed by Wongsri (1990), are generated and ranked according to those published heuristics and new ones. The match pattern is a new concept used as a fundamental selection unit in a combinatorial HENS problem. Also, the convention of a synthesis or design state is used in our synthesis method to explore new alternatives in a sequence of states. Match patterns are used as operators to operate on process streams, i.e. they map one design state to another. The advantages of this approach are its transparency, modularity, and simplicity.

4.1 The Nature of HEN Synthesis

A heat exchanger network design problem is, in its essence, a search problem. A search space called design space is a collection of all possible design points which are matches between hot and cold streams and utility streams that would totally or partially satisfy a set of design constraints. Usually, a design process is partitioned into several states since there are many alternative design points to choose from. A design or selecting operator will map one design state to another. In this option, all possible matches must be created a priori. An equivalent option is to use a match operator to match hot and cold streams. By this view, two important components in our search model are: (1) a collection of match operator (2) a design state.

4.1.1 Match Operator

A match or design operator is an action or procedure that map one design state to another design state. For most of the time, all the possible actions cannot be evaluated since they are so many. Therefore, we heuristically chose an action that is believed to be the best among many actions available.

4.1.2. Design State.

In a design process where many alternatives must be explored, a notion of design state is useful. A design state is a point on a solution path where new possibilities are created by an action in the previous design state. It is a point to stop and look ahead to explore new possibilities as well as to look back at the unselected old ones. When a match or matches are found, new alternatives for a match between a residual stream to the unmatched streams can be created. If in the current state no eligible match is possible, we have to backtrack to a previous state to choose a new alternative. Or, if a solution is found, we might also backtrack to previous states to find another solution.

To keep track of all decisions made in an exploration process of all available alternatives, a system to do the bookkeeping for the necessary information will be needed. Let us consider the following scenario:

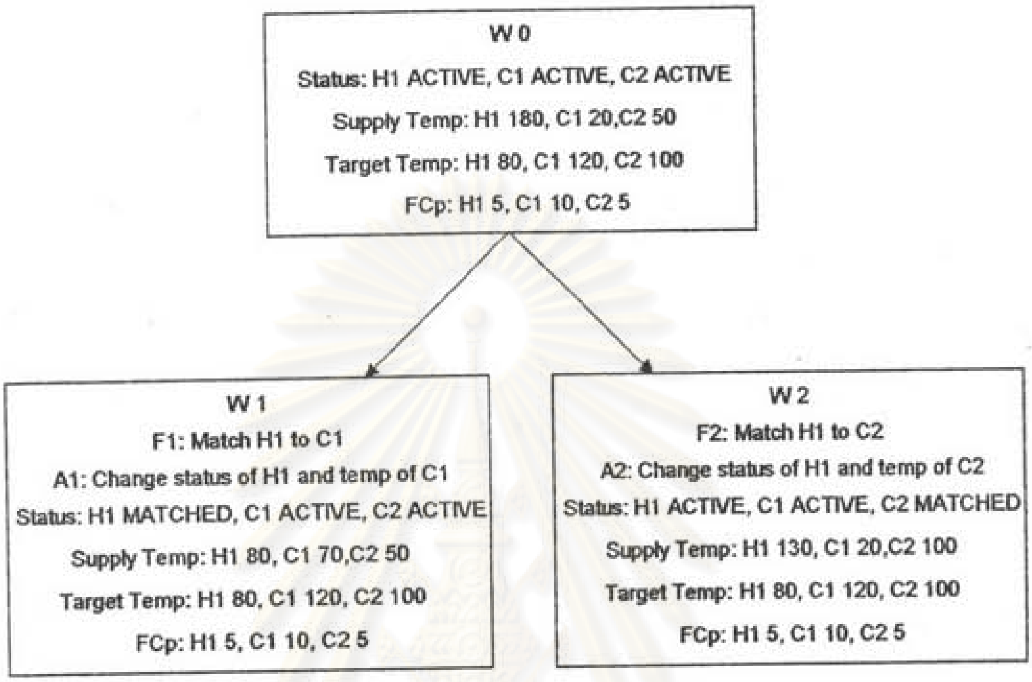


Figure 4.1 Concept of Design States

In Fig. 4.1 a starting situation may have many alternatives to be explored, different actions to be performed in different states of the design process. It may be begun by believing in information F1 and concluding A1, e.g. the action is taken and some artifacts are created, and then design context may be switched to believing in fact F2 and concluding A2. Environments must be created to support these different set of beliefs. A new state W1 is created for a design hypothesis A1 which will be true only in state W1 and its descendant states, but not true in others environment, e.g. W2, where another action A2 is chosen. For example, in Figure 4.1, a hot stream H1 is matched to a cold stream C2 with a larger heat load (F1) in W1. The status of H1 is matched and the status of C1 is still active and its supply temperature of C1 changes to a new value (A1). In W2, a match of H1 and C2 is chosen (F2). The heat load of C2 is less than H1 so the status of C2 is matched and the supply temperature of H1 is changed (A2). It can be seen that the facts about the streams H1, C1 and C2 are different in different states. Artifacts or designed objects can be mutually exclusive and believed in different states. In the above example, the match of H1 and C1 is created in W1, but in W2 it is H1 and C2. These streams must be accessed without any conflicts. For example, in W1 the status of H1 is matched and therefore it is not eligible to be matched with other cold streams, but in W2 its status is still active. So, in W2, H1 can be matched with other cold streams, but not in W1.

4.2 Heat Exchanger Network Synthesis

Usually, heat exchanger network synthesis is divided into 2 steps:

4.2.1 Network Targeting

The following important properties can be determined before the actual network is designed. They are used as the targets for a design.

1. The maximum energy recovery (or the minimum utilities). The minimum utilities can be calculated by constructing the problem table (Linnhoff and Flower, 1978a). The values depend on the minimum approach temperature, ΔT_{min}. The effect of ΔT_{min} on the generation of network configurations is such that, at its higher value, some configurations will be prohibited from appearing.

2. The minimum number of matches. The minimum number of matches is calculated from:

$$N_{match,min} = N_{hot\ stream} + N_{cold\ stream} - 1$$

If a problem is separated by pinch, this equation must be applied separately to each separated problem. If a matching procedure follows the 'tick-off' heuristics, a solution obtained will feature the minimum matches predicted by the above equation. In general, the cost of a minimum matches network solution is close to the minimum capital cost network (Nishida et al., 1977).

4.2.2 Network Synthesis

The heuristic approach finds a HEN solution in a sequence of steps. This can be viewed as using a match operator to map one design state to another. There can be many match operators or in contrast just one operator. Mehta and Fan (1987) use the following conditions in testing a match:

For a match at hot end position,

$$\Delta T_{he} \geq \Delta T_{min}$$

$$\Delta T_{he} - \min(L_h , L_c)\{1/W_h - 1/W_c\} \geq \Delta T_{min}$$

where $\Delta T_{he} = T_h^{supply} - T_c^{target}$, L = heat load, W = heat capacity flowrate, h = hot stream and c = cold stream.

For a match at cold end position,

$$\Delta T_{ce} \geq \Delta T_{min}$$

$$\Delta T_{ce} - \min(L_h , L_c)\{1/W_h - 1/W_c\} \geq \Delta T_{min}$$

where $\Delta T_{ce} = T_h^{target} - T_c^{supply}$.

Using one operator does not use any heuristic knowledge at all. To make use of heuristics we must discriminate among matches according to criteria or preferences. We can classify matches into several categories and give them different priorities. In this way, heuristics are used.

The HEN heuristics have appeared in the literature over two decades. The following is a summary of published HEN heuristics. The best known one is to make use of the pinch temperature which is called pinch heuristics (see Linnhoff and Hindmarsh, 1983). However, it alone cannot solve all problems. Other heuristics must be utilized in order to solve difficult problems.

4.3 Heuristics for HEN Synthesis

The heuristics are reported in a large number of publications. The heuristics for inventing HENs with minimum energy and investment costs are reported by Masso and Rudd (1969); Ponton and Donalson (1974); Rathore and Powers (1975); Linnhoff and Hindmarsh (1983); Jezowski and Hahne (1986) and Huang, Mehta and Fan (1988); etc.

The following are heuristics from the literature classified according to the design criteria.

The heuristics to minimize the capital cost (the number of heat exchangers):

Heuristic C.1 To generate a heat exchanger network featuring the minimum number of heat transfer units, let each match eliminate at least one of the two streams - a 'tick-off' rule (Hohmann, 1971).

Heuristic C.2 Prefer the matches that will leave a residual stream at its cold end if a problem is a heating problem, and at its hot end if a problem is a cooling problem. Obviously, a match of this type will feature the maximum temperature difference.

Heuristic C.3 Prefer matching large heat load streams together. The significance of this rule is that the control problem (a capital cost) of a match of this type (whether it is implemented by one or many heat exchangers) should be less than that of heating or cooling a large stream with many small streams.

The heuristic to minimize the energy cost (the minimum utility requirement):

Heuristic E.1 Divide the problem at the pinch into subproblems and solve them separately (Linnhoff and Hindmarsh, 1983). This is followed by the next three heuristics.

Heuristic E.2 Do not transfer heat across the pinch.

Heuristic E.3 Do not cool above the pinch.

Heuristic E.4 Do not heat below the pinch.

Heuristic E.5 Prefer a second type match. The residual of the second type match should be more likely to match with other streams. Cheaper utilities of lower temperature can be used for such residuals (Ponton and Donaldson, 1974).

Heuristic E. 6 Do the essential match first. In a cold end problem, if there is only one hot stream that can heat a cold stream to its target temperature, match these two streams. Otherwise, more than the minimum utilities will be required. The same is true for a hot end problem except that the role of hot and cold streams are reversed.

The laws of thermodynamics:

Rule T.1 In a heating problem, if a supply temperature of a cold stream is less than a target temperature of a hot stream by the minimum approach temperature (ΔT_{min}) or more and the heat capacity flowrate of a hot stream is less than or equal to the heat capacity flowrate of a cold stream, the match between these two streams is feasible.

(Immediately above the pinch temperature, the heat capacity flow rate of a cold stream must be greater than or equal to that of a hot stream.)

Rule T.2 In a cooling problem, if a supply temperature of a hot stream is greater than a target temperature of a cold stream by the minimum approach temperature, ΔTmin, or more and the heat capacity flowrate of a hot stream is greater than or equal to the heat capacity flowrate of a cold stream, the match between these two streams is certainly feasible. (Immediately below the pinch temperature, the heat capacity flow rate of a hot stream must be greater than or equal to that of a cold stream.)

Rule T. 1 and T.2 can be used as quick checks in match feasibility tests.

Rule T.3 For a situation different from the above rules, a match feasibility must be determined by checking whether the minimum temperature difference of a match violates the minimum approach temperature, ΔTmin, specified by the design.

4.4 Match Classification

In order to make use of the heuristics we must classify matches. The following criteria are considered important in this research:

1. Position of a match. Heuristic C.2 prefers a match at the cold end and Heuristic E.5 prefers a match at hot end. Pinch heuristics prefers a match at the cold end in a heating subproblem and a match at the hot end in a cooling subproblem. However, there are other possibilities. We can see that by using Heuristic C.1 or 'tick-off rule', there are four ways that two streams can match.

2. Heat capacity flowrate between hot and cold streams. See Heuristic T.1 and T.2.

3. Heat load between hot and cold streams. The heuristics that concern heat load state that one must match a large heat load hot and cold streams first. However, we want to propose two heuristics:

Heuristic N.1 We propose that for a heating subproblem, a match where the heat load of a cold stream is greater than that of a hot stream should be given higher priority than the other. The reason is that the net heat load in a heating subproblem is a deficit. The sum of heat loads of cold streams is greater than that of hot streams. The proposed match will likely be present in a solution.

Heuristic N.2 Conversely, we prefer a match where the heat load of a hot stream is greater than that of a cold stream in a cooling subproblem.

4. Residual heat load. No heuristic for this quantity have thus for appeared. Two new heuristics are introduced.

For a match in a heating problem that satisfies the heat load preference or Heuristic N.1:

Heuristic N.3 We prefer a match where the residual heat load is less than or equal to the minimum heating requirement.

For a match in a cooling problem that satisfies the heat load preference or Heuristic N.2:

Heuristic N.4 We prefer a match where the residual heat load is less than the minimum cooling requirement.

The reason behind these (N.3, N.4) is that if a residual heat load is less than a utility requirement, the residual may be matched to a utility stream. Thus, one has the possibility of eliminating two streams at once.

4.5 Match Patterns

A number of match patterns, a sub-structure description, are generated and ranked according to those published heuristics and new ones. A match pattern is a new concept used as a fundamental selection unit in a combinatorial HENS problem.

By the use of Heuristic C.1 which says 'let each match eliminate at least one of the two streams, there are four possible configurations that two streams can be matched according to the comparative heat loads between hot and cold streams and the positions of a match. We then classify match patterns into four classes and simply call them Class A, Class B, Class C, and Class D.

1. Class A. A match of this class is a Type I match which is a match at cold end position and the heat load of the cold stream is greater than that of the hot stream. This is upstream match. See Table 4.1.

For a heating problem, a Class A match is favored over the other Classes, because it leaves a cold process stream at the hot end (Heuristic N.1) and follows the pinch heuristics.

2. Class B. A match of this class is a Type II match which is a hot end match and the heat load of the hot stream is greater than that of the cold stream. This is an upstream match. Table 4.1.

For a cooling problem, a Class B match is favored over the other Classes, because it leaves a hot process stream at the cold end (Heuristic N.2) and also follows pinch heuristics.

3. Class C. A match of this class is a Type I match which is a cold end match and the heat load of the hot stream is greater than that of the cold stream. This is a downstream match. Table 4.2.

4. Class D. A match of this class is a Type II match which is a hot end match and the heat load of the cold stream is greater than that of the hot stream. This is a downstream match. Table 4.2.

A match of Class A or C will leave a residual at the hot end, while a match of class B or D will a leave residual at the cold end.

We will make use of Heuristics N.3 and N.4 to further subclassify matches of Class A and B and give the following subclass matches high priorities.

1. Subclass AH. A match of this subclass is a member of Class A, a heating problem where the residual is less than or equal to the minimum heating requirement.

2. Subclass BK. A match of this subclass is a member of Class B, a cooling problem where the residual is less than or equal to the minimum cooling requirement.

As it might be expected, we give a match of subclasses AH in a heating subproblem and BK in a cooling subproblem the highest priorities. See Table 4.1.

We further discriminate match patterns according to heat capacity flowrate. By following pinch heuristic, in a heating problem, we prefer a match where the heat capacity flowrate of a cold stream is greater or equal to that of a hot stream. For example, A[H] is a match in which the heat capacity flowrate of the cold stream is greater than that of the hot stream and the residual of the cold stream is matched to the heating utility.

Similarly in a cooling problem. we prefer a match where the heat capacity flowrate of the hot stream is greater or equal to that of the cold stream. For example, B[C] is a match in which the heat capacity flowrate of the hot stream is greater than that of the cold stream and the residual of the hot stream is matched to the cooling utility.

In summary, the rankings of the match patterns in a heating problem are AH, A[H], B[C], A[C], B[H], C[H], D[C], C[C] and D[H]. For a cooling problem, BK, B[C], A[H], B[H], A[C], D[C], C[H], D[H] and C[C].

4.5.1. Regular Match Operator

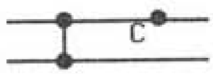
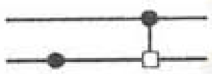
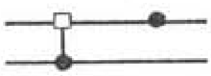
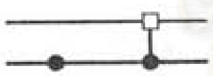
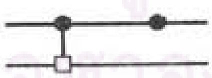
The defined match patterns are used in the regular matches, the split matches, the one to many streams and the special cases matches. These match patterns are use as operators or identifiers in HENS. Regular match operators are match patterns of two stream matches which require no splitting or any other qualification besides the descriptions of the patterns.

Regular match patterns and the testing conditions for Class A, B, C and D with [H] and [C] subclass characters are shown in Table 4.1 and 4.2.

4.5.2 Stream Split Match Operators

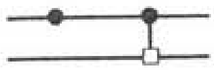
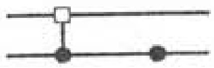
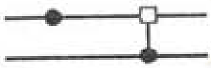
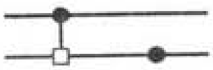
Devising stream split match operators is not an easy task, since there are few rules of how stream splitting can be done. Linnhoff and Hindmarsh (1983) list some observation rules for pinch matches when the splitting situation has been realized from observing the population and the heat capacity flowrate constraints. Stream splitting is very problem-specific so, split operators implemented in this work cannot be exclusive.

Table 4.1: Match Pattern Operators of Class A and B.

Match Operators	Conditions	Actions
Pattern AH 	$T^t_H \ge T^s_C$ $L_H \le L_C$ $T^t_H \ge T^s_C + L_H/W_C$ $L_C - L_H \le Q_{min}^{heating}$	Match H and C Status of H <= Matched $T^t_H \ge T^s_C + L_H/W_C$ $L_C <= L_C - L_H$
Pattern BK 	$T^s_H \ge T^t_C$ $L_C \le L_H$ $T^s_C \le T^s_H - L_C/W_H$ $L_H - L_C \le Q_{min}^{cooling}$	Match H and C Status of C <= Matched $T^s_H \ge T^s_H - L_C/W_C$ $L_H <= L_H - L_C$
Pattern A[H] 	$T^t_H \ge T^s_C$ $L_H \le L_C$ $W_C \ge W_H$	Match H and C Status of H <= Matched $T^t_H \ge T^s_C + L_H/W_C$ $L_C <= L_C - L_H$
Pattern B[C] 	$T^s_H \ge T^t_C$ $L_C \le L_H$ $W_C \le W_H$	Match H and C Status of C <= Matched $T^s_H <= T^s_H - L_C/W_H$ $L_H <= L_H - L_C$
Pattern A[C] 	$T^t_H \ge T^s_C$ $L_H \le L_C$ $W_C < W_H$ $T^t_H \ge T^s_C + L_H/W_C$	Match H and C Status of H <= Matched $T^t_H \ge T^s_C + L_H/W_C$ $L_C <= L_C - L_H$
Pattern B[H] 	$T^s_H \ge T^t_C$ $L_C \le L_H$ $W_H < W_C$ $T^s_C \le T^s_H - L_C/W_H$	Match H and C Status of C <= Matched $T^s_H <= T^s_H - L_C/W_H$ $L_H <= L_H - L_C$

Note: Cold stream temperatures are shifted up by ΔT_{min}.

Table 4.2: Match Pattern Operators of Class C and D.

Match Operators	Conditions	Actions
Pattern C[H] 	$T^t_H \geq T^s_C$ $L_H > L_C$ $W_H \leq W_C$	Match H and C Status of C <= Matched $T^t_H \Leftarrow T^t_H + L_C/W_H$ $L_H \Leftarrow L_H - L_C$
Pattern D[C] 	$T^s_H \geq T^t_C$ $L_H < L_C$ $W_H \geq W_C$	Match H and C Status of H <= Matched $T^t_C \Leftarrow T^t_C - L_H/W_C$ $L_C \Leftarrow L_C - L_H$
Pattern C[C] 	$T^t_H \geq T^s_C$ $L_H > L_C$ $W_H \leq W_C$ $T^t_C \leq T^t_H + L_C/W_H$	Match H and C Status of C <= Matched $T^t_H \Leftarrow T^t_H + L_C/W_H$ $L_H \Leftarrow L_H - L_C$
Pattern D[H] 	$T^s_H \geq T^t_C$ $L_H < L_C$ $W_H \geq W_C$ $T^t_H \geq T^t_C - L_H/W_C$	Match H and C Status of H <= Matched $T^t_C \Leftarrow T^t_C - L_H/W_C$ $L_C \Leftarrow L_C - L_H$

There are numerous possibilities that one can explore with this type of problem. The only constraint that seems reasonable is that the number of splits be minimal.

Stream splitting is needed when matching would result in violating minimum utilities requirement or the thermodynamic (minimum temperature difference) constraint. There are two cases of stream splitting reported:

1. Population constraint. The first case arises when the number of hot streams is greater than the number of cold streams in a heating subproblem and vice versa in a cooling subproblem (Linnhoff and Hindmarsh 1983).

2. Heat capacity flowrate constraint. Two different conditions indicate the need for stream splitting:

(a) In a hot side, the heat capacity flowrate of the hot stream is larger than that of the cold stream, and the target temperature of the cold stream is greater than the supply temperature of the hot stream, (otherwise, the hot stream can be matched to the cold stream at hot end position without having to be split).

(b) For a cold side, the heat capacity flowrate of the cold stream is larger than that of the hot stream , and the target temperature of the hot stream is lower than the supply temperature of the cold stream (otherwise the cold stream can be matched at cold end position without having to be split).

If should be noted here that the difference bound of heat capacity flowrate, e.g. for a hot side, for all pinch matches,

$$\sum^{N_C} W_{C,i} - \sum^{N_H} W_{H,j} \leq \sum^{N_{matches}} (W_{C,k} - W_{H,k})$$

suggested by Linnhoff and Hindmarsh is not necessarily a real constraint for splitting because on may find a match at the opposing position from the pinch where the heat capacity flowrate constraint is reversed. For example, in a hot side, for a match at the hot end position, the heat capacity flowrate of the hot stream being greater than that of the cold stream is favored. This match choice offers match opportunity when starting a match at pinch is not possible provided that the target temperature of the cold stream must be less than that of the hot stream.

There is still another constraint that will result in stream splitting besides the population and the heat capacity flowrate cases.

3. Temperature constraint. This is an essential split match. The situation arises when there is only one stream that can match to several other streams based on the temperature constraint. So, such a stream must be split otherwise, an unnecessary cooling or heating utility stream has to be matched to those constrained streams. For example, in a heating problem there are two hot streams whose target temperatures are lower than all of the supply temperatures of cold streams, except for one. That cold stream must be split and matched to the two hot streams.

The match pattern operators for these three cases are devised for the following situations.

1. Split one stream into streams to match with two opposing streams.

2. Split one stream into two streams to match with one opposing stream.

Various splitting match patterns for these cases are shown in Table 4.3, 4.4 and 4.5. Each pattern in Table 4.3 and 4.4 is used for only a certain combination of the population of heat capacity flowrate cases with subproblem types-heating or cooling. for example, a pattern A2, shown in Table 4.3(a), is for a heat capacity flowrate case in a heating subproblem. However, the pattern C2 , shown in Table 4.3(c), for heat capacity flowrate case in a hot side, can be used for a population case in a cold side. The pattern D2, shown in Table 4.4(f), for a heat capacity flowrate case in a cold side can be used for a population case in a hot side.

Matching Conditions. The testing equations for the splitting pattern are shown in the tables.

A value of heat capacity flowrate of a stream i superscripted by a star (W^*_i) is an equivalent value adjusted so that the end temperatures of stream i and stream j at a match starting point are different by ΔT_{min}.

1. Class A match. For a match at a cold end position and $L_H < L_C$. See Table 4.3 (a), (b) and 4.4 (a).

2. Class B match. For a match at a hot end position and $L_H > L_C$. See Table 4.3 (d) and 4.4 (d), (e).

3. Class C match. For a match at a cold end position and $L_H > L_C$. See Table 4.3 (c) and 4.4 (b), (c).

4. Class D match. For a match at a hot end position and $L_H < L_C$. See Table 4.3 (e), (f) and 4.4 (f).

The two splitting match pattern for a match of two streams are shown in Table 4.5. There are only two patterns possible for this case Other patterns are irrelevant. Both patterns can be used either in a hot side or cold side.

4.5.3 <u>One Stream Problem Operators.</u>

A match pattern operator for a case where there is only one stream to match to several streams is shown in Table 4.6. In order to be matched to all required streams, a single streams in a problem will be splitted when it is necessary. A special operator is introduced for this purpose.

Table 4.3: Hot Stream Splitting Match Pattern Operators.

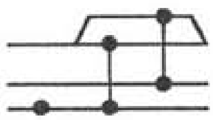
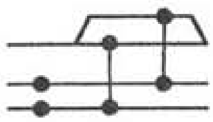
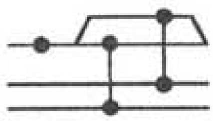
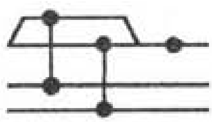
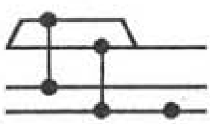
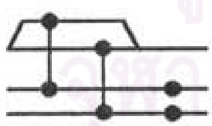
Match Operators	Conditions	Actions
Pattern A2H* 	$T^t_H \ge T^s_{C1}, T^s_{C2}$ $L_H \le L_{C1} + L_{C2}$ $L_H > L_{C1} \le L_{C2}$ $W_H \le W_{C1} + W_{C2}$	Split H with $W_{H1} = W_{C1} \Leftrightarrow L_{H1} = L_{C1}$ Match split Hs to C1 and C2 Set stream conditions, e.g. status, temps, etc.
Pattern A2H 	$T^t_H \ge T^s_{C1}, T^s_{C2}$ $L_H \le L_{C1} + L_{C2}$ $W_H \le W_{C1} + W_{C2}$	Split H with a ratio of $[W_{C1}: W_{C2}]$ Match split Hs to C1 and C2 Set stream conditions, e.g. status, temps, etc.
Pattern C2H 	$T^t_H \ge T^s_{C1}, T^s_{C2}$ $L_H > L_{C1} + L_{C2}$ $W_H \ge W_{C1} + W_{C2}$	Split H with a ratio of $[W_{C1}: W_{C2}]$ Match split Hs to C1 and C2 Set stream conditions, e.g. status, temps, etc.
Pattern B2H 	$T^s_H \ge T^t_{C1}, T^t_{C2}$ $L_H \ge L_{C1} + L_{C2}$ $W_H \ge W^*_{C1} + W^*_{C2}$	Split H with a ratio of $[W^*_{H1}: W^*_{H2}]$ Match split Hs to C1 and C2 Set stream conditions, e.g. status, temps, etc.
Pattern D2H* 	$T^s_H \ge T^t_{C1}, T^t_{C2}$ $L_H \le L_{C1} + L_{C2}$ $L_H > L_{C1} \le L_{C2}$ $W_H \le W^*_{C1} + W^*_{C2}$	Split H with $W_{H1} = W^*_{H1} \Leftrightarrow L_{H1} = L_{C1}$ Match split Hs to C1 and C2 Set stream conditions, e.g. status, temps, etc.
Pattern D2H 	$T^s_H \ge T^t_{C1}, T^t_{C2}$ $L_H < L_{C1} + L_{C2}$ $W_H \ge W^*_{C1} + W^*_{C2}$	Split H with a ratio of $[W^*_{H1}: W^*_{H2}]$ Match split Hs to C1 and C2 Set stream conditions, e.g. status, temps, etc.

Table 4.4: Cold Stream Splitting Match Pattern Operators.

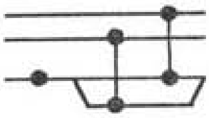
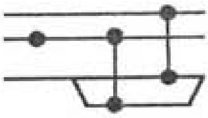
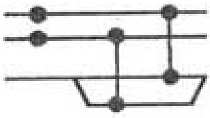
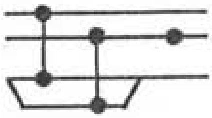
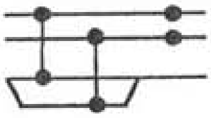
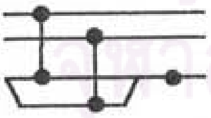
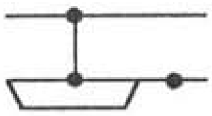
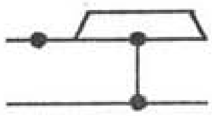
Match Operators	Conditions	Actions
Pattern A2$_C$ 	T^t_{H1} , $T^t_{H2} \geq T^s_C$ $L_{H1} + L_{H2} \leq L_C$ $W^*_{H1} + W^*_{H2} \leq W_C$	Split C with a ratio of $[W^*_{C1}: W^*_{C2}]$ Match split Cs to H1 and H2 Set stream conditions, e.g. status, temps, etc.
Pattern C2$_C$* 	T^t_{H1} , $T^t_{H2} \geq T^s_C$ $L_{H1} + L_{H2} > L_C$ $L_{H2} \geq L_{H1} < L_C$ $W^*_{H1} + W^*_{H2} \leq W_C$	Split C with $L_{C1} = L_{H1}$ Match split Cs to H1 and H2 Set stream conditions, e.g. status, temps, etc.
Pattern C2$_C$ 	T^t_{H1} , $T^t_{H2} \geq T^s_C$ $L_{H1} + L_{H2} > L_C$ $W^*_{H1} + W^*_{H2} \leq W_C$	Split C with a ratio of $[W^*_{C1}: W^*_{C2}]$ Match split Cs to H1 and H2 Set stream conditions, e.g. status, temps, etc.
Pattern B2$_C$* 	T^s_{H1} , $T^s_{H2} \geq T^t_C$ $L_{H1} + L_{H2} \geq L_C$ $L_{H2} \geq L_{H1} < L_C$ $W^*_{H1} + W^*_{H2} \geq W_C$	Split C with a ratio of $L_{C1} = L_{H1}$ Match split Cs to H1 and H2 Set stream conditions, e.g. status, temps, etc.
Pattern B2$_C$ 	T^s_{H1} , $T^s_{H2} \geq T^t_C$ $L_H + L_{H2} \geq L_C$ $W^*_{H1} + W^*_{H2} \geq W_C$	Split C with a ratio of $[W^*_{H1}: W^*_{H2}]$ Match split Cs to H1 and H2 Set stream conditions, e.g. status, temps, etc.
Pattern D2$_C$ 	T^s_{H1}, $T^s_{H2} \geq T^t_C$ $L_{H1} + L_{H2} \leq L_C$ $W^*_{H1} + W^*_{H2} \geq W_C$	Split C with a ratio of $[W^*_{H1}: W^*_{H2}]$ Match split Cs to H1 and H2 Set stream conditions, e.g. status, temps, etc.

Table 4.5: Splitting Match Pattern Operators.

Match Operators	Conditions	Actions
Pattern $D_{C1/2}$ 	$T^s_{H1} \geq T^t_C$ $L_H \leq L_C$ $W^*_H \leq W_C$	Split C with $W_{C1} = W^*_H$ Match split C1 to H Set stream conditions, e.g. status, temps, etc.
Pattern $C_{H1/2}$ 	$T^t_{H1} \geq T^s_C$ $L_H > L_C$ $W_H < W^*_C$	Split C with $W_{H1} = W^*_C$ Match split H1 to C Set stream conditions, e.g. status, temps, etc.

4.5.4 <u>Essential Match Operators.</u>

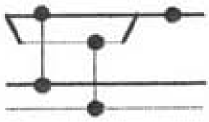
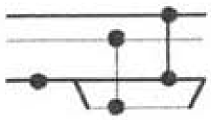
An essential match, to detect a match that must be done due to temperature constraint, must also be implemented in a rule system to avoid backtracking. For example, in heating problem, if there is only one cold stream that can cool a hot stream to its target temperature, then a match between such streams is an essential match. A situation where there are two cold streams to cool the coldest hot stream is also implemented. For a cooling problem the situations are reversed, e.g. an essential match is match of a single hot stream that can heat a cold stream to its target temperature.

4.5.5 <u>Large Stream Match Operator.</u>

An operator to match a largest hot stream and cold stream can be also implemented. One match operator for hot side and cold side subproblems, labeled L_H and L_C, are implemented.

Although matches by these operators can also be found by other match pattern operators, they may not be selected as early as desired, so the operators to detect these situations are included.

Table 4.6: One Stream Problem Match Operators

Match Operators	Conditions	Actions
Pattern B_{Hn} 	Heating problem No of cold stream = 1 $T^s{}_C \le T^t{}_{\text{coldest hot stream}}$	Find n necessary Cs to match them to H Split H and match to n Cs Set stream conditions, e.g. status, temps, etc.
Pattern A_{Cn} 	Cooling problem No of hot stream = 1 $T^s{}_H \le T^t{}_{\text{hottest cold stream}}$	Find n necessary Hs to match them to C Split C and match to n Hs Set stream conditions, e.g. status, temps, etc.

4.5.6 Utility Match Operators.

When there is only one kind of process streams left active, a solution is found. the process streams are automatically matched to utility streams. However, there is rule for detecting a situation that a certain stream must be matched to a utility stream since it cannot be matched to other streams because of the temperature constraint. This essential match operator will reduce a number of process streams to be considered and probably reduce the computation time.

4.6 Synthesis Procedure

A procedure of HEN synthesis by using match operators and a notion of a design state can be carried in steps as follows:

1. Push the match operators to a stack in proper order. This is a beginning of a new state.

2. While there is an operator on a stack.

(a) Pop a match operator from a stack to operate on process streams.

(b) If a match is found, exclude matched streams from a set of process streams. Change the condition of residual streams. Include the residual streams into a set of process streams. Go to a new design state (the first step).

3. If there are only hot or cold process streams left in the set of stream, a solution is found. If there are other solutions, they can be found by backtracking to the previous states to try the unused operators in those states.

4. If no matches is found in a current design state, backtrack to a previous state to try an available operator on the stack of that state. (Go to Step 2 in the previous loop). It is a recursive procedure here. If a match still could not be found, backtrack again to the more previous state.

The above sequences represent a loop of one design state. A total generation procedure a loop composing of these sequences.

The match operators and design state concept bring a new look to HEN synthesis by heuristic approach, e.g. more systematic and less sloppy. Match operators are classified according to match and stream properties, e.g. a match position, degree of heat loads, heat capacity flowrates, etc., and heuristically ranked according to published and new heuristics. A procedure-like sequence for network generation is written. This procedure can be automated as computer program and we will discuss it in the next chapter.