THE PINCH DESIGN METHOD FOR THE SYNTHESIS OF OPTIMAL HEAT EXCHANGER NETWORKS

by

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To my family ...

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ÖZET

Bu çalışmada, optimal ısı değiştirici şebekelerin tasarımını gerçekleştiren iki bilgisayar programı sunulmuştur. HEXNET ve DESIGN adı verilen bu programlarda en son geliştirilen yöntem olan Boğum Noktası tekniği kullanılmıştır. Isı integrasyonu yöntemlerinin tarihsel gelişimini vurgulamak amacıyla, Boğum Noktası tekniğinden önce geliştirilmiş metodlar detaylarıyla açıklanmıştır.

Yeni geliştirilen yöntemlerin geçerliliğinin sınanmasında yoğun olarak kullanılan problemler, bu çalışmada da çözülmüş ve uygun sonuçlar elde edilmiştir.

Hazırlanan programların, endüstrinin gereksinimlerine uygun olarak nasıl geliştirilebileceği açıklanmıştır.

ABSTRACT

In this work, computer programs, HEXNET and DESIGN, which are developed to perform the synthesis of optimal heat exchanger networks are presented. Most recently developed method, namely, the Pinch Technique is utilised for the preparation of these programs. A detailed outline of the previous methods is also included to emphasize the progress of the heat integration techniques.

Sample problems that have been widely used to prove the efficiency of a new method are solved by HEXNET and DESIGN. The resulting networks are in good agreement with the optimal structures.

Finally, recommendations are made to improve the compatibility of the programs with the needs of industry.

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a	cost parameter
A_{Ci}	area of the cooler (ft^2)
A_{Ei}	area of the j^{th} exchanger (ft^2)
A_{Hi}	area of the heater (ft^2)
A_{target}	target value for heat transfer area (ft^2)
b	cost index
CP	heat capacity flowrate (Kw/°C)
CPC	heat capacity flowrate of a cold stream (Kw/°C)
CPH	heat capacity flowrate of a hot stream (Kw/°C)
C_{Cj}	capital cost of the cooler ($/lb)
C_{Ei}	capital cost of the j^{th} exchanger ($/lb)
C_{Hi}	capital cost of the heater ($/lb)
C_{pi}	heat capacity flowrate of the i^{th} subnetwork (Kw/°C)
CPL	the larger CP of the two streams matched in an exchanger (Kw/°C)
CPS	the smaller CP of the two streams matched in an exchanger (Kw/°C
D_A,D_B	sought for design which maximizes the objective functions for problems A and B respectively
F	freedom of an exchanger
ΔH_i	heat deficit or surplus i^{th} subnetwork (Kw)
h_j	film or fouling coefficient of the j^{th} stream
L	number of loops
M	number of hot streams

m	slope of o line segment in a composite curve
N	number of cold streams
n	intercept of a line segment, corner point
NC	number of cold streams at the pinch
NH	number of hot streams at the pinch
NSN	number of subnetworks
O_A, O_B	economic design objective to be maximized in problem A and B, respectively
p	number of utility streams
Q	amount of heat removed from or addet to a stream or a subnetwork (Kw)
$\Delta Q_c, Q_c$	utility cooling supplied to a network (Kw)
$\Delta Q_H, Q_h$	utility heat supplied to a network (Kw)
q_j	head load of the j^{th} stream (Kw)
S	number of seperate components
S_{cj}	j^{th} cold stream
S_{hj}	j^{th} hot stream
S_{uk}	k^{th} utility stream
S_{ukl}	amount of utility spent at the l^{th} auxilary equipment
ΔT_{Lmi}	log-mean temperature difference for the i^{th} section (°C, °F)
ΔT_{min}	minimum approach temperature (°C, °F)
ΔT_s	smallest actual temperature difference within exchangers (°C, °F)
ΔT_{thres}	treshold temperature (°C, °F)
U	overall heat transfer coefficient(Btu/hr ft^2.°F)
u	number of units in a network
U_k	operating cost of utility stream S_{uk} per mass ($/lb)
U_{min}	minimum number of units in a network

z	the total number of process streams
α	area efficiency
δ	annual rate of return
θ	objective function

CHAPTER I

INTRODUCTION

Process synthesis is the step in design where the chemical engineer selects the component parts and how to interconnect them to create his flowsheet.

Engineers have been directed to better designs by the energy crisis experienced throughout the world in the early 1970s.The aim has become not only to save investment cost but also to use energy as efficiently as possible.So, the synthesis of optimal heat exchanger networks has become a major subject in this field.

The problem to be considered in this work has been first stated by Masso and Rudd [1].Later on, it has been redefined and formulated by many authors according to the manner how they attack to the problem.A general description can be given as follows.

M hot streams S_{Hi} (i=1,2,.....,M) to be cooled and N cold streams S_{Cj} (j=1,2,.....,N) to be heated are brought into contact in countercurrent shell and tube heat exchangers in such an order that they are carried from specified supply to specified target temperatures while the total cost of the network stays at its minimum.The heat capacity flow rates and the heat transfer coefficients of those streams are also given.Heat capacity flow rate of a stream is the product of its heat capacity and the mass flow rate.The temperature effect on heat capacity is usually ignored, but most algorithms can be easily modified to overcome this assumption.Effective heat transfer coefficients for all exchangers are assumed to be constant by some of the algorithms while some others use stream/stream match dependent coefficients.

Heat of vaporization, temperature and cost of steam, input and maximum allowable outlet temperatures of cooling water are the specifications of the utility streams S_{uk} (k=1,2,......,P) which are employed in auxilary heating and cooling.Here, it should be noted that the flow rates of these streams are not specified and typically not limitted.

Minimum allowable approach temperature (from now on, will be symbolized by ΔT_{min}) is generally assumed to be constant throughout the network.But, as in the case of heat transfer coefficients, some algorithms can be adapted to cover this case i.e. where ΔT_{min} is "match-dependent" and is not just a global value.This can be achieved by assigning ΔT_{min} "contributions" to streams. Finally, annual rate of return, a correlation to calculate the investment cost of an exchanger and equipment down time per year should be defined.

The above specifications for a heat exchanger network synthesis problem corresponds to the information typically available from a process flowsheet which has not as yet been heat integrated but for which the heat and meterial balances are completed.

Following the notation introduced above, the problem can now be expressed mathematically [2].

$$\Theta = \delta[\sum_{i} aA^{b}_{Ei} + \sum_{i} aA^{b}_{Hi} + \sum_{i} aA^{b}_{Ci}] + \sum_{k}\sum_{l} U_{k} S_{ukl} \qquad (1)$$

where, δ is the annual rate of return, a and b are the cost parameters, A_{Ei}, A_{Hi}, A_{Ci} indicate area of the i^{th} exchanger, steam heater and water cooler, respectively, U_{k} is the operating cost of utility stream S_{uk} per mass and finally, S_{ukl} is the amount of utility spent at the l^{th} auxilary equipment per year.

Since the main aim is to minimize the objective function (Θ), it is necessary to investigate the effects influencing the capital and operating costs separetely.

Figure 1.1 illustrates the influence of two basic thermodynamic effects on the former.As we reduce the driving forces in a network, investment cost increases due to larger heat transfer area .On the other hand, this will reduce the consumption of utility streams and decrease the overall heat load of the network.As it is known in common, such a decrease in heat load will cause a decrease in capital cost.This complex relationship may alter the expected results.Figure 1.2(a) is a network whose capital cost is expected to be very low since all heat transfer operations are achieved by utility streams.When energy is cheap and capital expensive, this configuration seems to be the most appropriate one.Figure

1.2(b) is another solution whose energy cost is expected to be very low since there is as much process heat recovery as is possible in preference to utility usage. In case of expensive energy and cheap capital, this solution will possibly be preferred if necessary analysis have not been carried out.

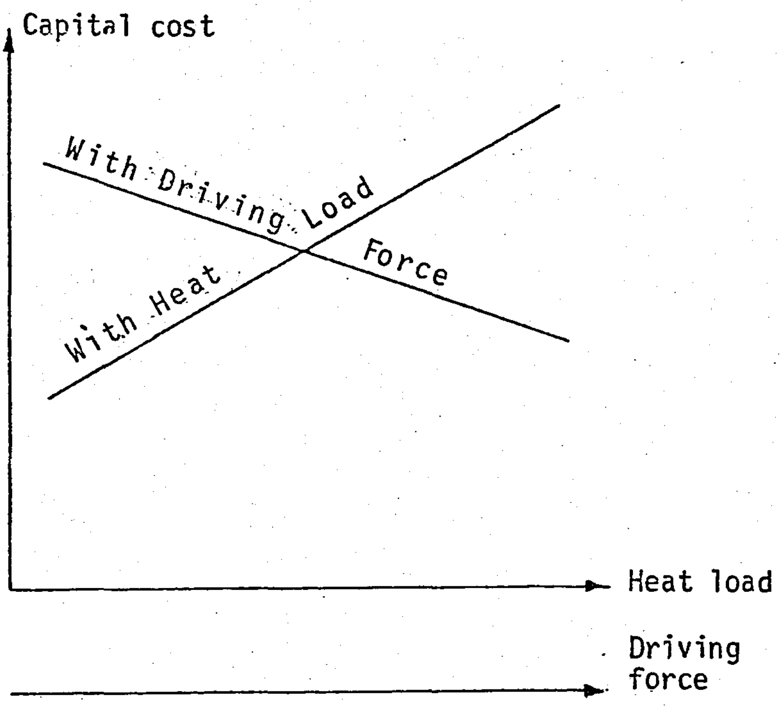
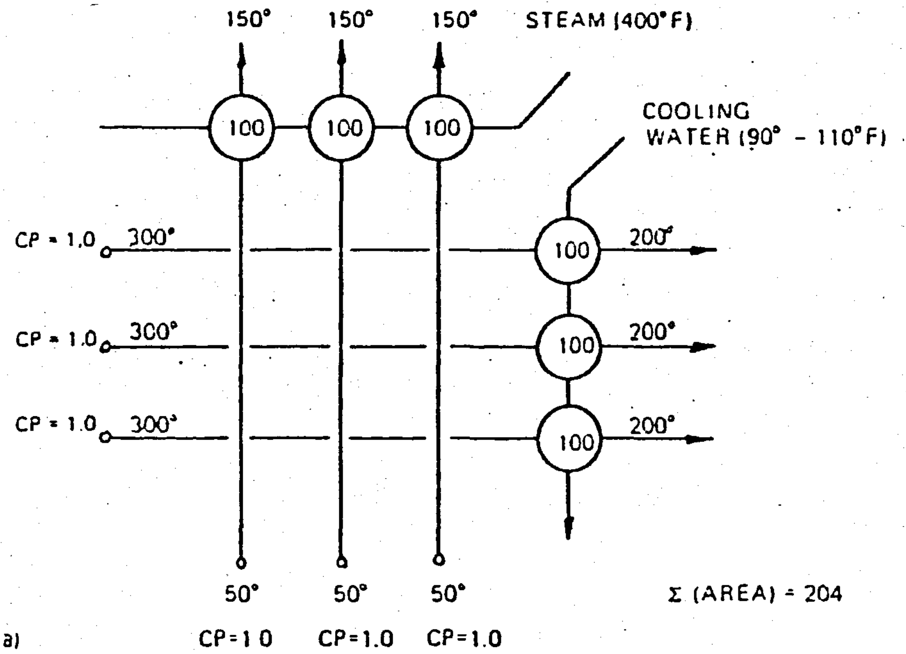
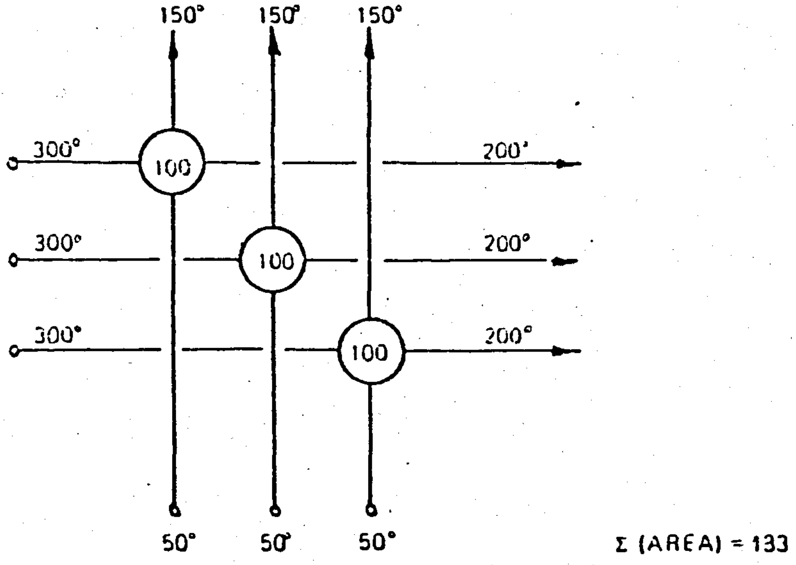


Figure 1.1- Effect of driving force and heat load on capital cost

Based on a uniform heat transfer coefficient and sensible steam and cooling water temperatures, the total surface area for both designs has been evaluated. What we see conflicts with our implicit assumption. The network for "minimum capital cost" turns out to have higher total surface area. This result can be explained by noting that the design without process recovery handles twice as much heat as is necessary. So the capital costs are increased even though the driving forces are large. This rather



(a) Area for minimum Capital Cost



(b) Area for minimum Energy Cost

Figure 1.2- Area for (a) minimum capital cost and (b) minimum energy cost

surprising influence of the total heat load on capital cost, now forces us to redraw Figure 1.1 by combining these two effects.

Figure 1.3 illustrates that, beyond a certain value for ΔT_{min}, the heat load effect begins to dominate and capital costs rise even though driving forces are increasing.

The same figure also shows the variation in energy cost with respect to driving forces.Sensitivity of the degree of heat recovery to driving forces, classifies the problems into two categories.Certain problems have constant utility consumption until the minimum allowed temperature difference, ΔT_{min}, is increased up to or beyond a treshold value, ΔT_{tresh}.For this reason such problems are called "treshold (or unpinched) problems".Figure 1.4 shows a simplified diagram in which ΔQ_H represents the utility heat supplied to a network and ΔQ_C the utility cooling.By simple heat balance,(ΔQ_C- ΔQ_H) will always correspond to the difference between the heat loads of the process streams to be heated and those to be cooled.The maximum feasible degree of energy recovery corresponds to the situation when both ΔQ_C and ΔQ_H are minimal.Figure 1.5(a) shows ΔQ_C and ΔQ_H as a function of ΔT_{min} for a hypothetical problem.Below ΔT_{min}= 20 °F, the utility heat loads are independent of ΔT_{min} whereas above 20 °F the load on both utilities increase.Since (ΔQ_C- ΔQ_H) is a function of the process stream heat loads which are not subject to change, ΔQ_H and ΔQ_C

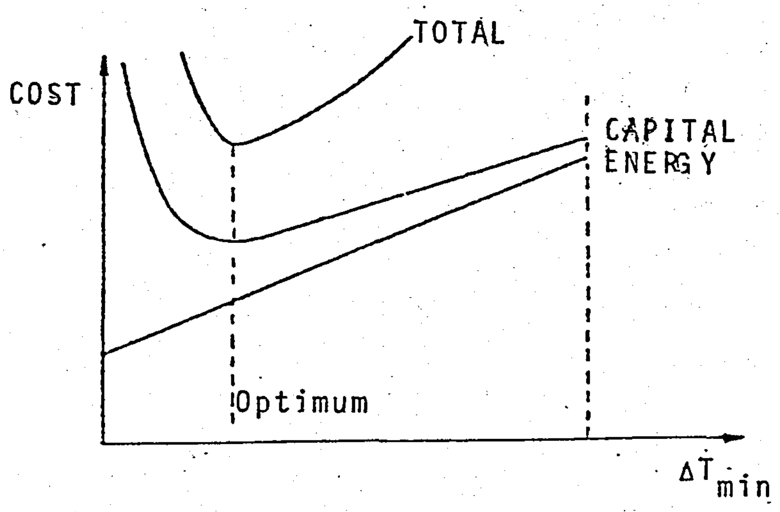


Figure 1.3- Network cost as a function of ΔT_{min}

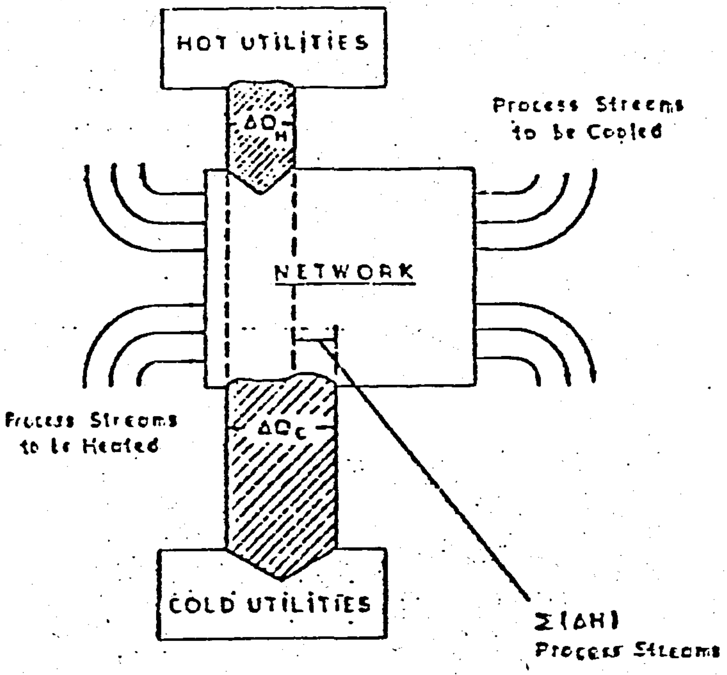


Figure 1.4- Maximum energy recovery [3]

increase with the same sensitivity beyond the treshold temperature, 20 °F.

Table 1 shows the treshold values of ΔT_{min} for some of the literature problems.It can be seen that the values computed by HEXNET which is one of the computer programs developed during this study, is in good agreement with the ones given in [3].From this table, problems 4SP2 (4 Stream Problem No.2), 5SP1, 6SP1, 7SP1, 7SP2 and 10SP1 emerge as being of the treshold ones.The remaining problems (i.e. TC1 (Test Case 1), TC2, TC3, 4SP1 and 10SP2) are of the second type, namely pinched problems.For this type of problems, utility vs. ΔT_{min} graph is given in Figure 1.5(b).

Back to Figure 1.3, we have to mention about another very important ΔT_{min} value which is located to the right of this minimum in capital.Beyond this point, there is no trade-off since both cost components increase as ΔT_{min} increases.Linnhoff et.al. [4] pointed out that "many state-of-the-art processes have designs in the rising region of the capital cost graph.Hence appplications of the techniques to state-of-the-art processes can lead to both energy and capital savings".The case studies mentioned in various references support this idea [4,5,6,7,8,9].

So far, the correlations between driving forces and the cost components have been examined without answering the question how to find the economic value of ΔT_{min}.As it is shown in Figure 1.3 , the total cost is obtained by summing up annuilised utility and capital costs.It passes through a minimum value which corresponds to a particular utility usage and ΔT_{min}.It should be noted that since

TABLE 1. TRESHOLD VALUES FOR VARIOUS PROBLEMS			
PROBLEM	REF. NO	SENSITIVITY TRESHOLD LIES AT ΔT_{min}= (° F)	
		GIVEN BY [3]	COMPUTED BY HEXNET
TC1	15	0	0.
TC2	15	0	0.
TC3	25	not mentioned	0.
4SP1	20	0	0.
4SP2	21	~ 46	46.43
5SP1	1	~ 43	42.86
6SP1	20	~ 65	65.25
7SP1	1	~ 49	49.40
7SP2	1	~ 51	50.00
10SP1	13	~ 72	71.62
10SP2	--	0	stream data not available

the network configuration may change with different values of the minimum temperature approach, the total cost function will in general be non-differentiable and hence a direct search procedure (e.g. golden section search as employed in [10]) should be used for this optimization.By costing several designs, it becomes possible to identify a ΔT_{min} in the region of optimum.Direct search procedure which is employed in this study is the Fibonacci search [11].HEXNET accepts a predetermined value for ΔT_{min} or it computes the optimal one.A detailed description of Fibonacci search is given in Appendix A.

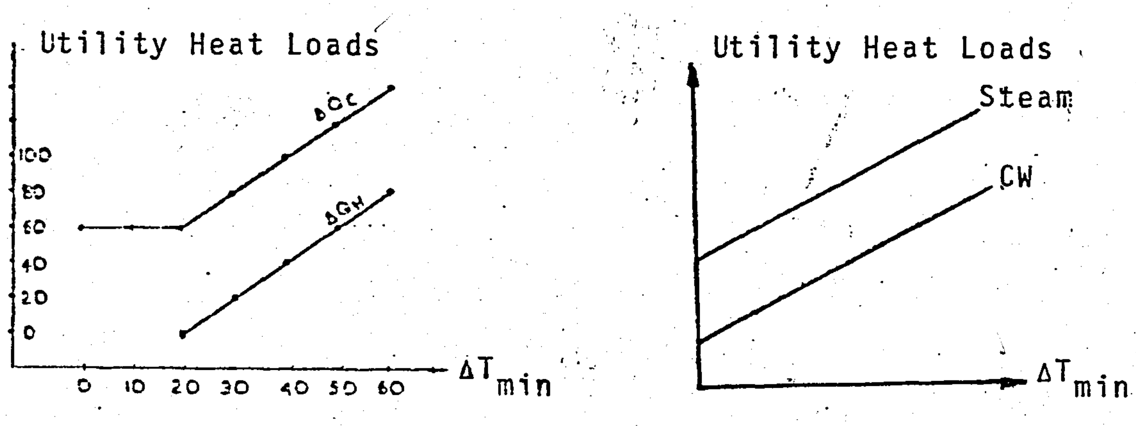


Figure 1.5- Utility requirements as a function of T_{min} (a) for treshold problems (b) for pinched problems [3,4].

Finally, an interesting footnote may be added to this discussion. All methods including Pinch Technique are the tools for preliminary design. They generally give the options to the engineer who decides on final network after following strict design procedures. As it is pointed out by Linnhoff and Vredeveld [8] "the user should always stay in control".

The contents of the following chapters are outlined below. Chapter II is a literature survey on heat exchanger network synthesis. Chapter III is an explanation of the computer programs namely, HEXNET and DESIGN which are developed during this study. Chapter IV tabulates the stream data for some problems, their solutions obtained by the computer programs mentioned above and comparisons with different algorithms. Chapter V includes conclusions, remarks and recommendations. Finally, Appendix A explains Fibonacci search method which is employed in this study to optimise minimum approach temperature.

CHAPTER II

LITERATURE SURVEY

Chapter II which is devoted to the literature survey on design methods for the synthesis of heat exchanger networks, is formed by two sections.Algorithms developed prior to "pinch technique" are outlined in the first section.From now on, these algorithms will be referred as "previous methods".Pinch method which is the most recently developed heat integration technique will be discussed in detail in the second part.

2.1 PREVIOUS METHODS

Previous methods will be summarized by following the classification of Nishida et.al. [12] who have given a detailed review on process synthesis most recently.

Having given the complete description of heat exchanger network problem in Chapter I, methods of problem representation becomes the first subsection to be discussed.

2.1.1 Problem Representation

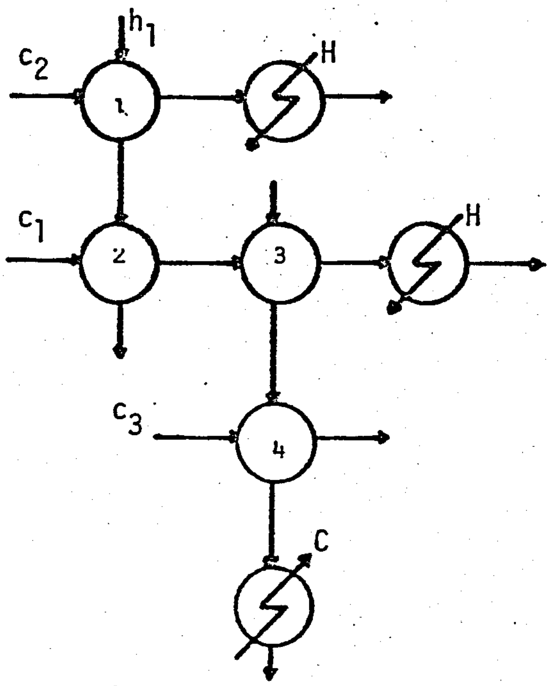
A variety of different representations have been used in developing heat exchanger networks. Perhaps the oldest is the "temperature/enthalpy diagram". Temperature (ordinate) for each stream is plotted against its enthalpy (abcissa). The enthalpy scale is only relative; thus, streams may be moved to the right or left on this diagram. A match between two streams is represented by placing a cold stream (one which is to be heated in the match) directly below a hot stream (one which is to be cooled). Where the streams overlap, the match takes place. By construction, the overlapped portions are in heat balance. The match is also thermodynamically feasible as the hot stream is hotter than the cold stream in all places along the match. The vertical distance between the streams is the temperature difference experienced along the match. Construction of a temperature/enthalpy diagram will be discussed further in section 2.2.2 by using an example problem (see Figure 2.13 (b)).

A second representation introduced by Pho and Lapidus [13] is the "simple match matrix ". The authors refer to an exchanger network with "n" heat exchangers as a "n" step network. At a given synthesis step a pair of process streams will be matched and identified by the (i,j) entry of a matrix "A" whose row and column denote the cold and hot streams, respectively. If at the n th synthesis step, the cold stream c_i is matched to the hot stream h_j, the (i,j) entry is set equal to "n", or a(i,j)=n; otherwise the entry is left blank.

$$A = \begin{bmatrix} a(i_1, j_1) \;\ldots\ldots\; a(i_1, j_{mh}) \\ \vdots \qquad\qquad\qquad \vdots \\ a(i_{nc}, j_1) \;\ldots\ldots\; a(i_{nc}, j_{mh}) \end{bmatrix}$$

A "M" step network will therefore have M non-zero entries whose values range from 1 to M.The last row and column of a synthesis matrix denote whether the process streams require the service of heaters (H) or coolers (C) to meet their temperature specifications. Those streams which have met their terminal temperatures during the earlier synthesis and therefore require no service from the heaters and coolers in the final synthesis step are denoted by the symbol (T). The remaining block of the synthesis matrix is the "A" matrix defined earlier.Figure 2.1 illustrates a sample network and its synthesis matrix.Also, the use of synthesis matrix during the generation of a decision tree diagram is illustrated in following sections (Figure 2.5).

A third representation is the "heat content diagram" of Nishida, Kobayashi, Ichikawa [14].In Figure 2.2, the heat content diagram representing a simple syntesis problem that contains two hot streams S_{h1}, S_{h2} and two cold streams S_{c1} and S_{c2} , is shown. In general, the vertical axis of the diagram represents the input and output temperatures of hot and cold process streams, or the input and output temperatures of heating and cooling



	h_1	h_2	
c_1	2	3	H
c_2	1		H
c_3		4	T
	T	C	

Figure 2.1- A sample network and its synthesis matrix

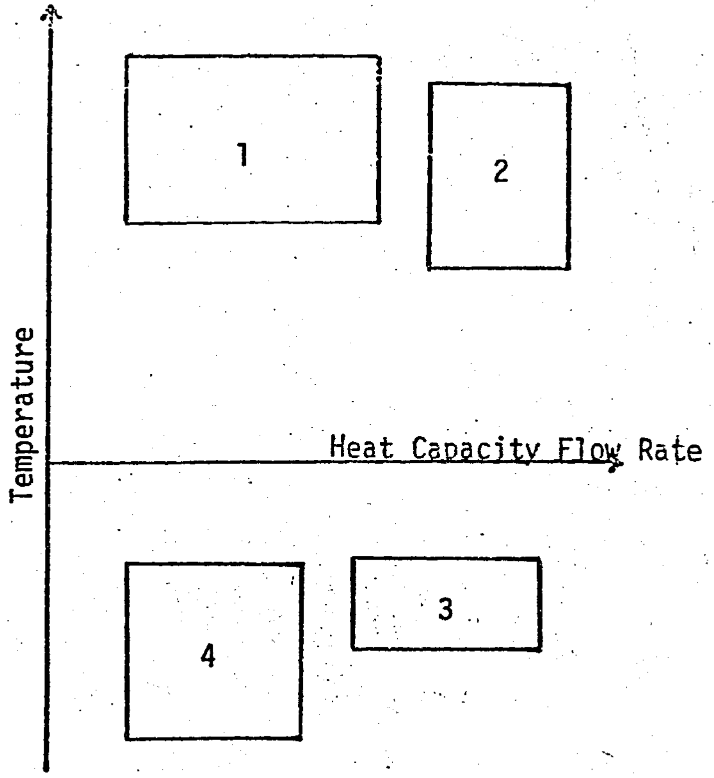


Figure 2.2- Heat content diagram

utility streams. The origin of the temperature scale is set separately such that all hot streams and heating utilities are located above the horizontal axis and all cold streams and cooling utilities below the horizontal axis. The horizontal axis represents the relative magnitude of heat capacity flow rates of various streams.On the diagram, each stream is represented by a block.The area of a given block corresponds to the amount of heat to be removed from or added to the stream in order for it to reach its desired output temperature.

$$\text{Area} = Q = \int_{T_1}^{T_2} CP\, dT \qquad (2)$$

In this equation, Q represents the amount of heat removed from or added to a stream which is cooled or heated from T_1 to T_2. Here, note that the temperature/enthalpy diagram is the integral form of the heat content diagram.For convenience, both process and utility streams should be drawn on the diagram such that heating utilities and hot streams are located in a decreasing order of their input temperatures above the horizontal axis; while cooling utilities and cold streams are located in a decreasing order of their output temperatures below the horizontal axis.As it is indicated earlier, in most cases, the output temperatures and the heat capacity flow rates of utility streams are both unknown before their exchanges with other process streams.Thus, in representing a given synthesis problem, a heating or cooling utility stream is denoted initially by a point on the diagram, with the ordinate value specifying its known input temperature.Also, on the diagram, a heat exchange between a hot and a cold process stream is indicated by assigning the same number or letter to the corresponding hot and cold blocks. Note that since the heat contents of hot and cold process stream to be exchanged must be the same, the hot and cold blocks designated by the same numbers or letters on the diagram must have the same area.Likewise, both above and below the horizontal axis of the diagram, the total number of hot and cold blocks representing the exchanged hot and cold process streams as well as their corresponding total heat contents should also be the same.Finally, division of a block either horizontally or vertically is permitted on the diagram. The former corresponds to the multiple heat exchange, and the latter represents the stream splitting.

Another convenient representation by Linnhoff and Flower [15] directly represents the network structure, Figure 2.3.Hot streams run from left to the right at the top, and the cold streams run from right to the left at the bottom.A match between streams is indicated by placing a pair of circles on each of the streams and connecting them by a vertical line.This explains why the diagram is so called; "Grid Representation".Beneath the symbols for heaters, coolers and exchangers, heat loads are noted in appropriate units. Temperatures may be shown

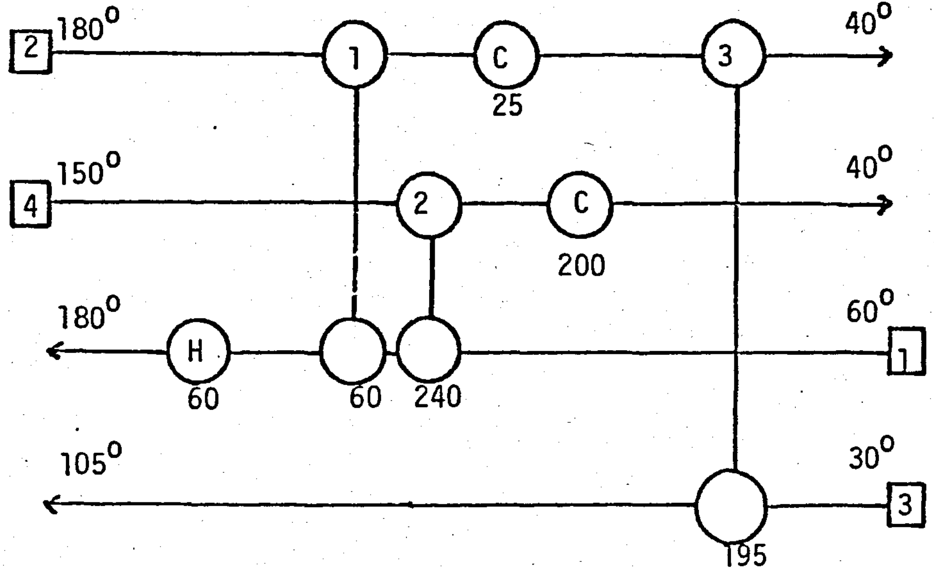


Figure 2.3- Grid representation

against each stream and so may heat capacity flow rates. The exchangers may be numbered at one of their nodes.Though, understanding the significance of pinch temperature has affected the structure of grid representation, conventions described above are still valid for drawing these diagrams.Figure 2.11 may give an idea about the new look brought to grid representation by the Pinch Technique.

2.1.2 Synthesis Algorithms

The heat exchanger network synthesis problem can be conveniently partitioned into the following three major steps.

I. Preanalysis to set targets, limitations.

II. Network invention.

III.Evolution.

The first two of these steps can be further subdivided, both into the same set of substeps, but with each emphasizing the substeps differently.The substeps are as follows.

A. Partition the synthesis problem.

B. Merge equivalent heat sources, sinks.

C. Select stream/stream matches.

D. Select network capable of producing desired matches.

Here, it will be shown how the different algorithms, published for heat exchanger networks, fit into and contribute to the above problem "generalization."

2.1.2.1 Preanalysis

Preanalysis involves establishing targets for the network to be designed.These targets are: (1) the least amount of utilities which are needed; (2) the minimum area required;and (3) the probable, but not guaranteed, fewest number of heat exchangers needed.Experience has shown that networks satisfying targets, (1) and (3) are very attractive solutions [4,7].Target (2) is usually only approached, but not reached by the optimal solutions.

Least utility targets have been set five ways, some of which only establish lower bounds.Table 2 lists the alternatives. An obvious bound (UB-1) is to establish the difference in heat required for heating the cold streams and the heat available for cooling the hot streams.The bound has sometimes been refined slightly (UB-2) where one accounts for cold streams which require heating above any temperatures available by the hot process streams or any hot streams requiring cooling below any temperature available by cold process streams [2,16,17]. However, exact targets (UB-3) are possible which can always be met, and these account for both the difference in heating and cooling required and the temperature levels of the streams [15].

TABLE 2. MINIMUM UTILITY BOUNDS USED IN LITERATURE [12]

UB-1: Net difference between heating needed for cold streams and cooling needed for hot streams.

UB-2: Same as UB-1 but modified to account for portions of hot (cold) streams colder (hotter) than any existing cold (hot) process stream.

UB-3: Exact bound accounting for uniform minimum allowed approach temperature.

UB-4: Exact bound accounting for uniform minimum allowed approach temperature and user stated disallowed stream/stream matches.

UB-5: Same as UB-4 but with match dependent minimum allowed approach temperature.

The essence of the method (UB-3) to establish the minimum utility bound is to merge all hot streams into a single hot "superstream" and all cold into a single cold "superstream."Plotting these two superstreams on a temperature/enthalpy diagram, one moves the cold superstream under the hot until the minimum vertical distance exactly equals the minimum ΔT allowed anywhere in the exchanger network [18].

$\Delta T_{min} = 0$ constitutes an impractical case requiring infinite heat transfer area (see Equations 3 and 17).The unmatched portions of each of these streams represent the minimum heating and cooling required (Figure 2.13(b)).Besides this graphical solution, an analytical procedure, namely "Problem Table Method" will be discussed further in section 2.2.1.1.

Cerda in coorperation with Linnhoff, Mason and Westerberg [19] calculates minimum utility requirements.The extension permits one to exclude matches between designated pairs of streams, either in total or over certain ranges of temperature (UB-4).This application becomes very important in some special cases (e.g. the streams may be both vapor and far apart, leading to very costly piping requirements, a leakage may lead to a dangerous situation etc.).He also extended the ideas to allow the minimum allowed temperature to differ with each stream/stream pair (UB-5).(UB-5) is also explained by Linnhoff et.al.[4].Each stream is assigned a ΔT_{min} contribution and the minimum approach temperature for a particular exchanger is calculated by summing the contributions of the matched streams.Thus if liquid streams are assigned 5 °C and gas streams 10 °C, then a liquid/liquid match has a ΔT_{min} of 5+5=10 °C, a liquid/gas match has a ΔT_{min} of 5+10=15 °C and a gas/gas match has a ΔT_{min} of 10+10=20 °C.

The target of "minimum area" can be discovered rather quickly using the superstreams [14]. If exactly matched by the introduction of utilities as needed and if all heat transfer coefficients are assumed equal, the so called "minimum area" solution corresponds to a countercurrent exchanger designed for these superstreams. The area calculation involves integrating

$$A = \frac{1}{U}\int_{1}^{2}\frac{dQ}{\Delta T} \qquad (3)$$

where A is the area, U is the heat transfer coefficient, Q the heat transferred and ΔT the vertical distance between the two superstream curves at the point that the incremental heat dQ is transferring.An alternative equation which is developed for the case of non uniform heat transfer coefficients will be discussed in sub-section 2.2.2 (Equation 17).

Prior to explaining how to find the number of fewest heat exchanger units,it will be beneficial to discuss the importance of that target.

General cost expression of exchangers is as follows,

$$C_{Ei} = a\, A^{b}_{Ei}. \qquad (4)$$

By using this expression, one can write the following inequalities [2]:

$$a(A^{b}_{E1}+A^{b}_{E2}+..+A^{b}_{Em}) \geq a(A_{E1}+A_{E2}+\;..+A_{Em})^{b} \qquad (5\text{-a})$$

$$a(A^{b}_{E1}+A^{b}_{E2}+..+A^{b}_{Em}) \geq$$

$$a(A_{E1}+A_{E2})^{b}+a(A_{E3}+..+A_{Ei})^{b}+a(A_{Ei+1}+..+A_{Em})^{b} \qquad (5\text{-b})$$

Note that for either inequalities

$$0 \leq b \leq 1.$$

These imply that without increasing the total heat transfer area of exchangers, the investment cost of exchangers can be reduced if several units can be combined together as a single one, or a smaller number of exchangers are to be used.Here, inequality 5-a corresponds to the case where m exchangers are reduced to a single unit; inequality 5-b represents the case where m exchangers are reduced to three exchangers.Obviously the same idea is also applicable in reducing the investment cost of heaters or coolers.

An application of Euler's general network theorem is utilized by Hohmann and later by Linnhoff to determine the target of fewest number of exchangers [3,4].

$$u = N+L-s \qquad (6)$$

where,

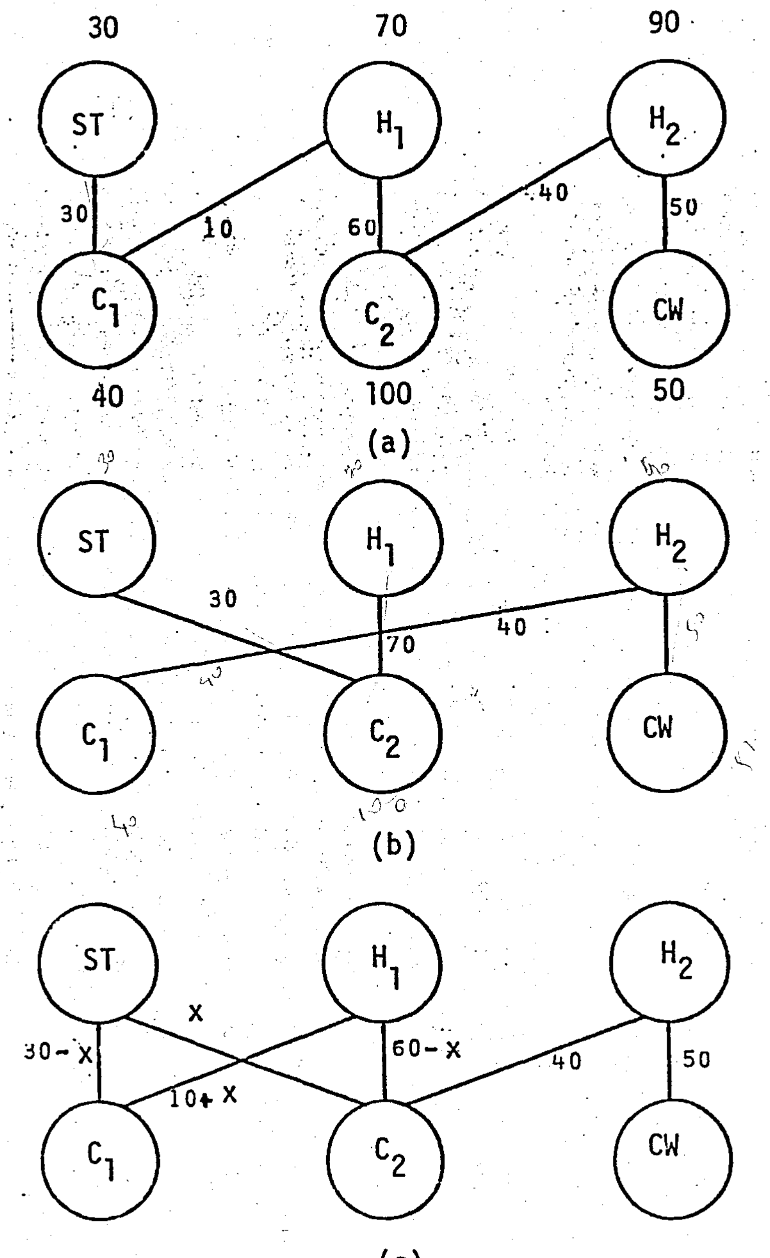
u = number of units (including heaters and coolers)

N = number of streams (including utilities)

L = number of loops

s = number of separate components.

A hypothetical problem ,Figure 2.4, having two hot streams and two cold streams will be used to clarify the meanings of a loop and a separate component.Both utility heating and utility cooling are required.Every stream is indicated by a circle with the heat load given beneath.Each line connecting a hot and a cold stream represents an exchanger.Note that the total system is in enthalpy balance, i.e. the total heat surplus of hot streams equals the total heat deficit of cold streams



(a)

(b)

(c)

Figure 2.4- Principles of subsets and loops

(190 units). Assuming that temperature constraints will allow any match to be made, the matches can be put as follows ,Figure 2.4(a). Matching steam with cold (1) and maximising the load completely satisfies or "ticks off" steam, leaving 10 units of heating required by cold (1). Matching cold (1) with hot (1) and maximising the

load on this match so that it ticks off the 10 units of residual requirement on cold (1), leaves 60 units residual heat available from hot (1).Matching hot (1) with cold (2) ticks off hot (1) and leaves cold (2) requiring 40 units of additional heating.Now, matching hot (2) with cold (2) and maximising load, ticks off cold (2) and leaves hot (2) with 50 units of residual heat load.The last match should be between hot (2) and cooling water.As it is mentioned earlier, the system is in enthalpy balance and this is why one hot and one cold stream with the same heat content and requirement left behind.The last exchanger will satisfy both streams while the previous ones were elimating only one of the pair.This explains why the number of exchangers is one less than the total number of streams.Figure 2.4(a) corresponds to the case in which L=0 and s=1.This is the case which is mostly encountered and leads to the targeting equation

$$u_{min} = N-1 \qquad (7)$$

In Figure 2.4(b), a design is shown having one unit less.In this case, two separate components exist and both of them are in enthalpy balance individually.Steam, cold (2) and hot (1) form the first subset while cold (1), hot (2) and cooling water form the second.What this means is that for the given data set one can design two completely separate networks, with the Equation 7 applying to each individually.This situation is termed "Subset Equality" and very important since one does not want to overlook the chance to reduce the number of units in practical context. It is often possible to deliberately modify heat loads of streams and group streams together so as to create such situations. Finally, in Figure 2.4(c) a design is shown having one unit more than the design in Figure 2.4(a), the new unit being the match between steam and cold (2). The extra unit introduces what is known as a "loop" into the system. That is, it is possible to trace a closed path through the network. Starting, say, at the hot utility, the loop can be traced through the connection to cold(1), from cold (1) to hot (1), from hot (1) to cold (2), and from cold (2) back to steam. The existance of the loop introduces an element of flexibility into the design. Suppose the new match, which is between steam and cold (2), is given a load of (X) units. Then by enthalpy balance, the load on the match between steam and cold (1) has to be (30-X), between cold (1) and hot (1) (10+X), and between hot (1) and cold (2) (60-X). Clearly X can be anything up to a value of 30, when the match between hot utility and cold (1) disappears. The flexibility in design introduced by loops is sometimes useful, particularly in "retrofit design."

The preanalysis steps for the existing methods are compatible with the four substeps (A to D) stated earlier. To establish utility bounds and/or area bounds, the problem is usually partitioned according to key temperature intervals [15]. First if ΔT_{min}, a user prescribed "minimum approach temperature," is added to all cold stream temperatures, the prescribed inlet and outlet temperatures for all streams, including utilities, are ordered into decreasing order. Each pair of temperatures on the list represents an interval for the hot streams. Cold stream intervals are the same but with the temperatures decreased by ΔT_{min}. If no stream/stream matches are excluded by the designer, within each interval the contributions for each substream can be merged to create hot and cold superstreams.When the problem table method will be discussed in section 2.2.1.1, a numerical example will be given to illustrate how to define these temperature intervals and subnetworks.

The last step taken to calculate minimum utilities is to select the stream/stream matches among these merged substreams. With only one hot stream and one cold stream, matching is a trivial step. No actual network need to be proposed, so step D is not required for preanalysis.

2.1.2.2 Network Invention

As stated earlier, the network invention step can also be subdivided into four substeps: (A) partitioning the synthesis problem; (B) merging equivalent heat sources, sinks; (C) selecting stream/stream matches; and (D) selecting the heat exchanger network capable of producing the desired matches. Not all of these substeps are necessarily a part of each of the published algorithms.

Partitioning, if it occurs, is of two types.The problem may be partitioned by temperature intervals, as explained already for the preanalysis step. The TI method of Linnhoff and Flower [15] uses this partitioning. If one has done a preanalysis and has located where in the problem a temperature pinch point exists, one may also partition the overall problem into two problems, one above the pinch and one below. Heat cannot be exchanged between these two partitions, if one wishes to develop networks requiring minimum utility usage. This partitioning was implicitly a part of the TI method [15] and used explicitly by the Pinch Technique.

A class of algorithms (e.g., Nishida et.al. [14]) next proposes that streams with equivalent heat be merged. This step is exactly that of producing superstreams mentioned earlier and thus moves these algorithms into the class performing a preanalysis to find the minimum area target for a problem.

Next, the different algorithms select which stream/stream (or superstream/superstream) matches to make. Many accomplish this step as a sequence of match decisions, while others make their stream/stream match decisions in parallel. We shall discuss this step at length becouse of the different ways the various algorithms accomplish this step.

2.1.2.2.1 Sequential Match Decision Algorithms

TABLE 3. SEQUENTIAL MATCH OPTIONS [12]

Search Strategy Employed:

SS-1: Total Enumeration
SS-2: Brach and Bound
SS-3: Heuristic
SS-4: Other

Heuristics Used: (If SS-3 Employed)

HR-1: Select hot stream with highest inlet temperature and cold stream with highest target temperature.
HR-2: Select hot stream with coldest target temperature and cold stream with coldest inlet temperature.
HR-3: Select match giving least value to ΔT_{ave}.
HR-4: Select match giving least value to estimated upper bound on overall network cost.

Match Restrictions:

MR-1: Disallow stream splitting
MR-2: Disallow stream/stream rematching (cycling)
MR-3: Disallow if match precludes predicted minimum utility usage
MR-4: Disallow if match precludes network having predicted fewest number units

Stream Heat Selection Decisions:
(h = for Hot Stream, c = for Cold Stream)

HS-1 h,c: Take heat from or supply heat to hottest end of stream.
HS-2 h,c: Take heat from or supply heat to coldest end of stream.
HS-3 h,c: Take heat from or supply heat to intermediate portion of stream.

For algorithms in this class, the principal questions are the search strategy employed, how to select the next match, and what is meant by a match.

Table 3 lists the variety of search strategies (SS), of heuristics for selecting the next match (HR), of match restrictions (MR), and of heat selection rules (HS) used by the various algorithms.

The essence of algorithms which develop the network as a sequence of match decisions is to develop a tree of networks, where the initial node is the network with no process stream/process stream matches. All heating and cooling is done directly by utilities by this node. The children of this node are all networks containing exactly one process stream/process stream match. Their children contain exactly two process stream/process stream matches, etc.

One of the earlier algorithms [13] suggests developing the entire tree of networks which their rules allow to be generated, but the tree becomes excessively large for a ten stream problem. They suggest a fallible "look ahead" procedure to reduce to a feasible size, the number of branches of the tree to be examined. As a summary, the procedure is defining an evaluation function to each of the nodes generated during the synthesis; such a function evaluates the quality of each node.It can be used to pull the search toward the optimal node by first generating the most promising node, while the remaining nodes are either retained for future expansion or simply deleted from further consideration.The evaluation function can be exact or merely heuristic; in the first case optimality is guaranteed while in the second there is no guarantee of finding the optimal node.Since the heuristic procedure would be expected to be much easier to compute, Pho and Lapidus try to define a heuristic function which generates a partial enumeration to the entire tree while still providing for the possibility that the optimal node can be located.Figure 2.5 illustrates the reduced decision tree for problem 4SP1.Several redundant nodes are eliminated by the procedure developed by Pho and Lapidus.To aid in interpretation, the blank entries in the rows and columns of the A-matrix whose corresponding streams have reached their final output temperatures are denoted with the symbol asterisk (*) and if the matching is infeasible (e.g. temperature constraint is violated) the corresponding entry is filled with the symbol (~).

Some other algorithms propose using a branch and bound scheme [16,17] to search the tree.To use this scheme a lower bound on cost has to be estimated for all nodes emanating from a given node. This lower bound is usually the annuilized capital cost for the heat exchangers already involved in the network plus a lower bound on the cost of utilities still required (calculating minimum utilities using one of the utility bounds UB-1 to UB-3). Lee, Masso and Rudd used Branch and Bound method to approach extremely difficult design problems gainfully by branching from the difficult problem to other simpler problems, and generate the solution to design problems which are unsolvable when attacked frontally [20].The more easily solved alternate design problem B must be selected to bound the original problem A in the following way.If $O_A(D)$ is the economic design objective to be maximized in problem A by

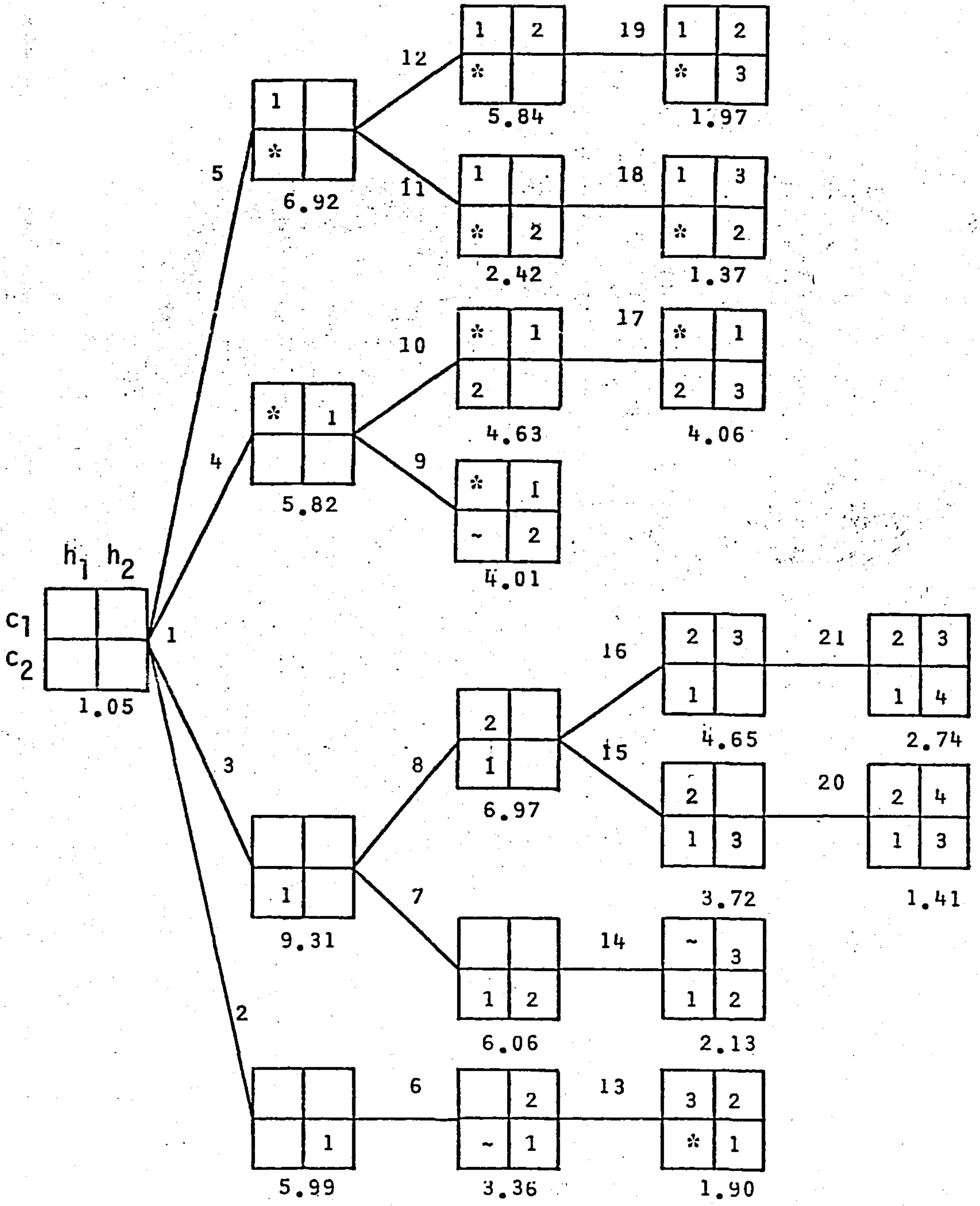


Figure 2.5- Reduced decision tree for 4SP1

adjusting design D, D_A is the sought-for design which maximizes that objective, and $O_B(D)$ is the economic objective for the alternate problem B, if Equation 8 holds, problem B bounds A

$$O_B(D_A) \geq O_A(D_A) \qquad (8)$$

and D_A must be feasible for problem B.

That is, if the optimal solution to problem A were available and applied to problem B, that design would be feasible for problem B (satisfying all the technical constraints but not neccessarily at maximum objective function), and exhibit an equal or greater value for the economic objective.If so, problem B is an upper bound for A.After solving the bounding problem B, the optimal design being D_B, one should check whether this solution is also an optimal solution to the original unsolvable problem A or not.This test is done by the help of Equation 9:

$$O_B(D_B) = O_A(D_B) \qquad (9)$$

The fastest, but obviously most fallible, algorithms simply use one of the heuristics HR-1 to HR-4 to select a single next match.

A number of possible matches are disallowed by match restrictions (MR). For example, no stream splitting may be allowed (MR-1) or no stream rematching (MR-2). Rematching is when two streams exchange heat in two or more noncontiguous exchangers. If the algorithm was developed with an awareness that one can calculate the minimum utility usage bound (UB-3), it may eliminate any match which if made, would preclude reaching this bound (MR-3).Detection of such a match is done by making the match and then running a "preanalysis" on the unmatched streams to detect the minimum utility usage needed for them. If this prediction indicates an increase in the use of utilities, the match can be excluded (see section 2.2.3.3 for further details).

The algorithm may also disallow matches not leading to the predicted fewest number of heat exchanger units (MR-4).To reach such a solution each match made in the sequence must eliminate one of the two streams entirely and leave a single residual from the other. If the match cannot accomplish such an elimination becouse of temperature limitations, it need not be considered.These type of algorithms may be fallible in some cases where a compulsory match should be materialized though none of the streams can be ticked-off due to temperature constraints.5SP1 is a standart problem which constitutes a good example for such a situation.The problem data and network configurations of 5SP1 are given in Chapter IV.

The heat selection options (HS-1h,c to HS-3h,c) can have a profound effect on the network developed. Earlier algorithms matched the hottest portion of the hot stream against the coldest portion of the cold (HS-1h/HS-2c). This match decision is the most thermodynamically irreversible, leaving the hot end of the cold stream and/or the cold end of the hot stream for subsequent heating or cooling. Ponton and Donaldson [21] appear to be first to advocate matching the hot end of the hot stream against the hottest portion of cold stream (HS-1h/HS-1c). This heat selection rule is quite reasonable for above ambient networks as it is more thermodynamically reversible and it tends to allow the

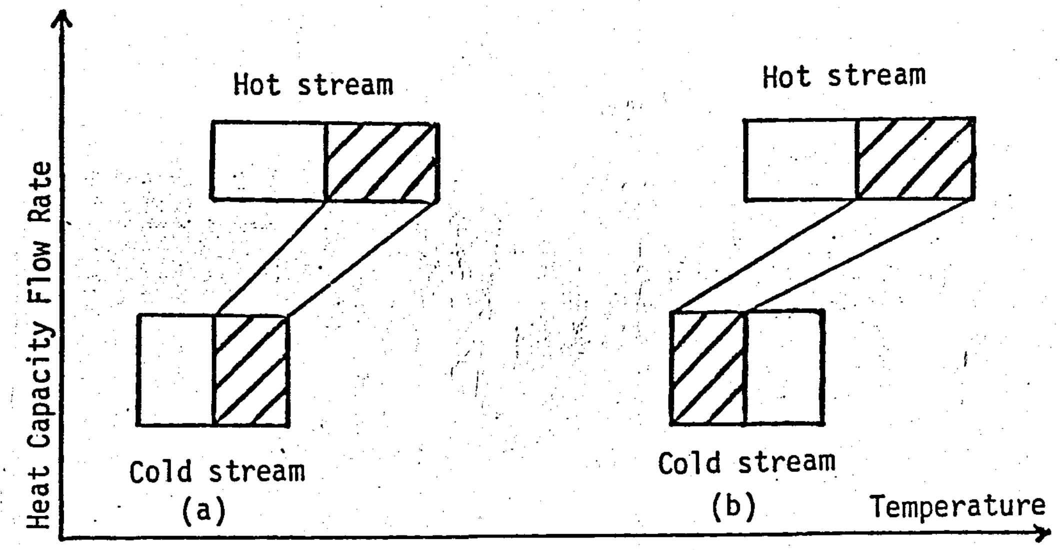


Figure 2.6- Examples to heat selection decisions (a) HS-1h/HS-1c (b) HS-1h/HS-2c

lower-temperature hot utilities to be used. It does this by using lower-temperature cold utilities.This trade is sensible since above-ambient hot utilities are more expensive than above-ambient cold ones.Figure 2.6(a) illustrates HS-1h/HS-1c decision reached by Ponton and Donaldson.Heat selection option preferred by earlier algorithms is shown in Figure 2.6(b).

Some of the later papers describe sequential algorithms simultaneously requiring minimum utility usage (MR-3) and accomplishing all this in the predicted minimum number of heat exchanger units (MR-4) [12].

2.1.2.2.2 Simultaneous Match Decision Algorithms

The first approach that will be discussed in this section is one of the earliest published, using a method based on the "assignment algorithm" in linear programming [12,22]. In this approach, every stream is first partitioned into a set of usually quite small substreams, each substream having a heat content of "Q" units. Some algorithms require this partitioning to be sequential (equivalent to no stream splitting), whereas some others permit parallel partitioning (equivalent to stream splitting). "Q" is chosen so every stream is partitioned, to an adequate approximation, into an integer number of substreams.It is specified as an approximate value of the greatest common divisor of the heat exchange duties of the hot and cold streams. Utilities are also added as a generous number of substreams, each again with a heat content of "Q" units. The assignment problem is to assign hot substreams to cold ones in a manner which minimizes the sum of the costs associated with each assignment (see Equation 1). Constraints precluding certain assignments are readily added, and they reflect thermodynamic considerations (the hot substream must be hotter than the cold one). They could also represent user restrictions. Very quicly a large number of substreams and constraints are generated, even for small problems. The "assignment algorithm" of linear programming is effective at handling large problems.

The cost of an assignment is the weakest aspect of this approach. It can easily include the cost of utilities by assigning, as part of the cost for a match involving utility substream, the cost of "Q" units of that utility. The cost must also include the annualized cost of heat exchanger area, but area costs should reflect overall heat exchanger size, since large exchangers cost much less per unit area than small ones. That is, taking cost parameter "b" as unity does not express the actual cost, especially for small sized exchangers.The cost index may be far from unity if such exchangers are to be used.

The solutions resulting from this approach require further work as they simply provide one with assignments of the small substreams to substreams. It is up to the user to translate these into a practical set of heat exchangers corresponding only approximately to the substream assignments. This method apparently results in quite good answers.

The second simultaneous match decision algorithm is the TC algorithm of Linnhoff and Flower and Linnhoff [12,23]. This algorithm will generate all heat exchanger networks satisfying match restrictions MR-1 (no stream splitting), MR-3 (minimum utility usage) and MR-4 (fewest number of heat exchanger units). It is readily shown that such networks are acyclic; that is, if one were to disregard the direction of stream flows and then trace the pipework for such a network, one cannot find a path which starts with a given heat exchanger and which subsequently returns to it. Figure 2.4(a) may aid in believing this property.An apparent disadvantage of the method is the fact that where solutions of the kind specified above do not exist, the method will yield no answer.This situation would be encountered in problems where full heat recovery is difficult to achieve, i.e., where more than the minimum number of units have to be used and/or streams have to be split for a satifactory solution.Flower and Linnhoff [23] propose a mixed solution method to handle such problems.Since, the TI (Temperature Interval) method leaves little choice in subnetwork design where heat recovery is difficult, and offers alternative designs in subnetworks only when heat recovery is easier, their general approach becomes one of synthesizing partial networks which ensure maximum energy recovery by the TI method with suitably identified remaining problems.These remaining problems can then be tackled with the TC method.

The TC algorithm first predicts the minimum amount of utilities along with required utility streams, then like an odometer ticking off the miles, it generates all stream/stream match structures which do not contain cyles.Three constraints should be kept in mind at this step:

i) Target Temperature Feasibility

Each match bringing a stream to its target temperature must be with a stream or service whose supply temperature is compatible with that target temperature.

ii) Topological Feasibility

Each stream or service must be used in at least one match.

iii) Heat Load Feasibility

If a stream or service is matched only once, its partner must have an equal or larger heat load.A natural consequence of this is that in any feasible network, the stream or the service with the largest heat load must have at least two matches.Further, the second largest stream or service must have at least two matches, unless matched against the largest stream or service etc.

These constraints are necessary conditions for feasibility but not sufficient in themselves.One should calculate the heat loads for each match, and eliminate entire structures if the heat loads suggested by these matches are not all positive (they require that heat must always transfer from hot streams to cold ones). Finally the algorithm systematically creates heat exchanger networks for each structure. No stream splitting is allowed. The temperatures are calculated and the structure is kept only if the temperatures are satisfactory throughout; that is, temperature driving forces larger than some prescribed minimum ΔT occur in all matches.

Finally, two recent algorithms which in fact should not be included under the heading of "Previous Methods" will be discussed.These algorithms do recognize the pinch concept but reach final solutions by employing simultaneous match decisions.

Duran and Grossmann [24] propose a procedure for solving nonlinear optimization and synthesis problems of chemical processes simultaneously with the minimum utility target for heat recovery networks.The unique characteristic in this approach is that variable flow rates and temperatures of the streams can be handled within a nonlinear optimization framework.Ideally, in order to account for the interactions between the chemical process and the heat recovery network, both should be optimized simultaneously. However this rigorous approach would lead to a difficult combinatorial problem.Therefore, in order to simplify the problem Duran and Grossmann suggest the optimization of the chemical process simultaneously with the minimum utility target for heat integration of the process streams.In this way, the resulting design exhibits flow rates and temperatures of the streams that guarantee maximum heat integration.

The same article also includes a smooth approximation procedure developed by the authors.Instead of using a nondifferentiable optimization, Duran and Grossmann apply this procedure to obtain continuity of the derivative by replacing the structural nondifferentiabilities with a suitable smooth approximation function.

Another recent approach by Floudas, Ciric and Grossmann [10] enables the consideration of stream splitting, bypassing, matching in series, matching in parallel, matching in series-parallel and matching in parallel-series. In order to show how such a task is realised, consider an example problem having one cold (C_1) and three hot streams (H_1, H_2, H_3). Figure 2.7 illustrates the stream superstructures that can be postulated for the problem above. By equating the heat capacity flow rates of some of the branches to zero, one can reach a variety of alternative sequences.

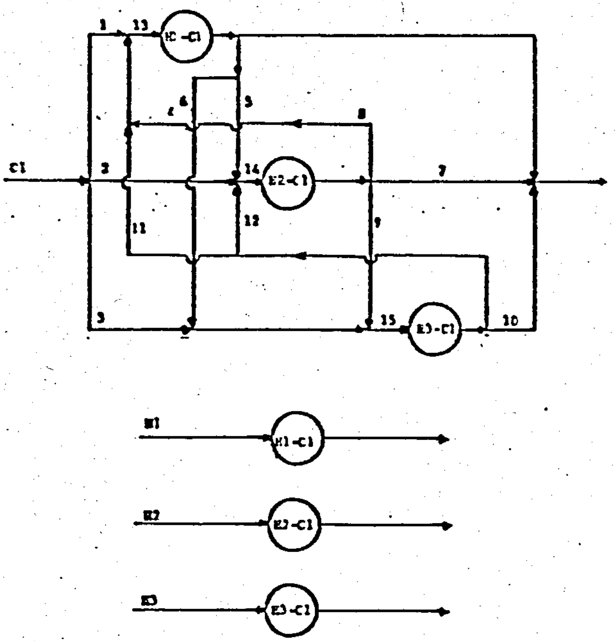


Figure 2.7- Stream superstructures [10]

The synthesis strategy can be outlined in five steps. The first step is the determination of minimum utility cost as well as the location of the pinch points. This step is taken by a linear programming (LP) transshipment model. At the second step, a mixed-integer linear programming (MILP) transshipment model is solved to determine the minimum number of matches and the heat exchanged at each match.Step three is the derivation of superstructures.For each stream an independent superstructure is developed and these are then combined into an overall superstructure.At step four, a nonlinear programming (NLP) formulation is presented for the automatic generation of network structures with minimum investment cost.Finally, at step five, final network configuration is obtained.

As it is given at the begining of section 2.1.2, the last step of network invention is the selection of configuration that is capable of producing desired matches. For the sequential match decision algorithms this step is accomplished at the same time that the stream/stream matching decisions are made; for the parallel match algorithm, it is a separate step. The algorithm of Nishida et. al. [14], where equivalent heats are merged, has only selected which merged heat sources are to supply heat to which merged heat sinks. Subject to guidelines given, it is up to the user to choose among the alternatives possible to develop the actual network.

2.1.2.3 Evolution

Many publications present steps to aid in improving a heat exchanger network, once one is developed.

Nishida , Liu, and Lapidus [2] present a set of evolutionary rules to improve networks generally developed with the aid of the earlier minimum area algorithms of Nishida, Kobayashi and Ichikawa [14]. The minimum area algorithm requires one to develop a network containing far too many actual heat exchangers, and the evolutionary rules were to aid one to reduce the number of exchangers.The suggested rules are as follows:

i) Compare the areas (heat contents) of various hot and cold blocks in the heat content diagram.Delete the exchanger, the heater, or the cooler with the smallest area or the least amount of heat exchange by increasing the heat duty of the rest of the process and/or utility streams.Repeatedly apply this procedure until the total cost of the resulting network can no longer be reduced.

ii) If a network contains a local sub-network where a hot (or cold) stream matches with the same cold (or hot) stream which it has matched before, delete either of these two repeated matches.

iii) Replace the stream splitting with the stream un-splitting (or the multiple heat exchange).Match the hot and cold streams in the un-splitting network in a decreasing order of their arithmetic averages of input and output temperatures.

It should be noted that these rules are to be applied in their numerical order; that is, rule (i) should be tried before rules (ii) to (iii), etc.

The ED (evolutionary development) method of Linnhoff and Flower [15] is a set of rules to aid one when making small changes to a heat exchanger network, such as those developed by their TI method. The rules tell one how to detect easily if the suggested small step will lead to a thermodynamically feasible network.Before listing these evalutionary rules, a parameter should be introduced which is called "freedom of a heat exchanger",

$$F = CPL\ (\Delta TS - \Delta T_{min}). \qquad (10)$$

In this equation, ΔTS is the smallest actual temperature difference within heat exchangers and CPL is the larger CP of the two streams matched in an exchanger.Parameter F has the same physical dimension as a heat load.The purpose of introducing this parameter is to ease methodical investigation of the effects of changes in the positions of exchangers.The maximum load which can be shifted through an exchanger in a simple case is equal to the freedom as defined by Equation 10. Shifts of smaller load will merely reduce the freedom of the exchanger by the size of the load.

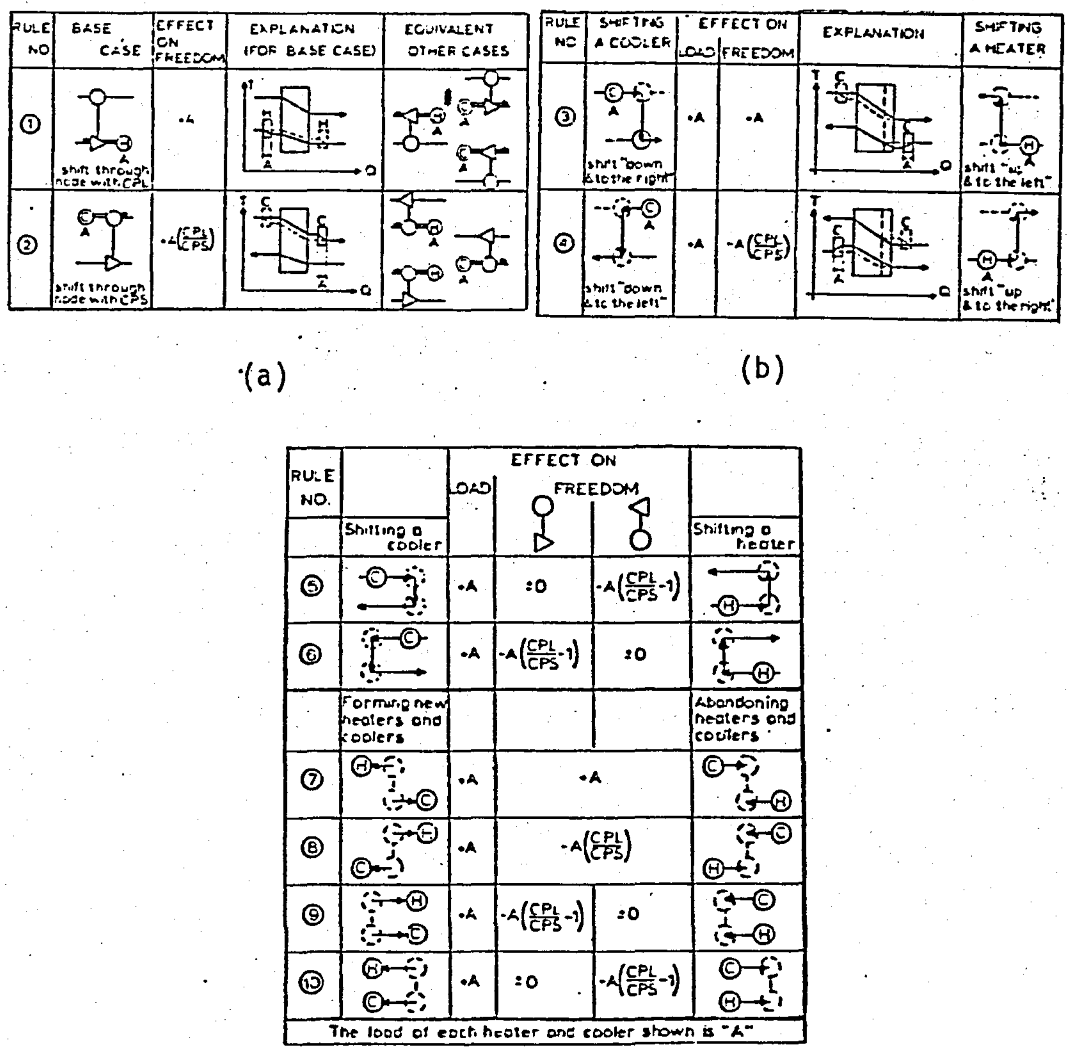
Figure 2.8(a) summarizes the effects that simple shifts of heaters and coolers have on an exchanger's freedom; shifts according to rule No.1 (that is, along the stream with the larger CP) will alter the exchanger's freedom by the heat load of the cooler (or heater) which is shifted.The effect of shifts according to rule No.2 (that is, along the stream with the smaller CP) is greater by the factor CPL/CPS (where CPS is the smaller CP of the two streams matched in an exchanger).To make it easily recognizable which one of the two streams has the larger CP, the following conventions are developed by Linnhoff and Flower [15]:

1) To situate an exchanger's reference number in the node on the stream with the smaller CP.
2) To replace the node on the stream with the larger CP by a triangle as a qualitative indication of the temperature profile within the exchanger.Thus, it will always point, like an arrow, towards that side of the exchanger at which the smallest actual temperature difference is found.In the case of equal CPs for both streams, two circles may be retained.For exchangers in which the freedom is zero (that is, ΔT_{min} is reached), the triangle or one of the circles (in case of equal CPs) may be blacked out.

In Figure 2.8(b), two more rules are given.They are concerned with cases in which the heater (or cooler) in question is shifted from one stream to another.Such shifts not only affect the freedom of the exchanger but also affect its load.On the other hand, the effects are independent of the heat capacity flow rates so the exchangers are not shown in full detail in Figure 2.8(b).

It is clear that the direction of each shift shown in Figures 2.8 (a) and (b) may be reversed and that coolers may be shifted instead of heaters or vice versa.The effects on load and freedom of the exchanger concerned would be equal in magnitude to the effects shown in

Figures 2.8 (a) and (b) but opposite in sign. Furthermore, those combinations of rules No 1. to No 4. are shown in Figure 2.8(c) which have been claimed to be of practical value. Each of these combinations, again, could be applied with reversed direction and reversed sign.



(a) (b)

(c)

Figure 2.8- Rules of the ED method (a) Shifts along streams of heaters and coolers through exchangers (b) Shifts from one stream to another of heaters and coolers through exchangers (c) Further rules for shifting and merging [15]

2.2 PINCH METHOD

The most recently developed heat integration technique is the pinch method [3,4,6,7,8,9,25,26,27,28]. The method involves two phases: data analysis and network design.

Data analysis yields targets that correspond to the performance characteristics of the economic optimum network.These targets are invaluable when dealing with complex integration problems, and give confidence to an engineer's current design or stimulate the engineer to search for a better solution.Furthermore, the targeting procedures give a new insight into a very simple but fundamentally important decomposition of the original problem into several parts.

TABLE 4. DATA FOR SAMPLE PROBLEM

STREAM NUMBER	STREAM TYPE	TEMPERATURE (°C)		HEAT CAPACITY FLOW RATE (kW/°C)
		SUPPLY	TARGET	
1	HOT	270	160	3.0
2	HOT	250	130	1.5
3	COLD	120	235	2.0
4	COLD	180	240	4.0

Having obtained the targets, one can start to design the network with the most constrained part, namely the pinch.This constitutes the second phase of the method.

Some concepts (i.e. temperature/enthalpy diagram, grid representation, problem table method) which make use of both previous algorithms and pinch technique are highlighted in section 2.1 and will be discussed in details here.

2.2.1 The Pinch

In this sub-section the phenomenon of the pinch itself. is discussed.The discussion is in five parts.First, the procedure of locating the pinch is given.Second, the physical significance of the pinch and its implications on utility usage are described.Third, a powerful representation for both the pinch and heat exchanger network stream data is explained.Fourth, the industrial problems are considered from this method's point of view.Finally, the implications of pinches on capital cost are discussed.

2.2.1.1 Locating the Pinch

The task of locating the pinch is illustrated by using an example problem for which stream data are given in Table 4. Problem Table algorithm of Linnhoff and Flower [15] will be first explained to show how this task is performed.

The feasibility of complete heat exchange between all hot and cold streams is an important feature of the algorithm.To ensure this feasibility a minimum approach temperature difference should be allowed between the hot and cold stream temperatures anywhere in the system.This

1	2	3	4	5	6	7		8	
# of SN	COLD (°C)		HOT (°C)	CP of SN (kW/°C)	ΔH (kW)	Accumulated		Max. Permissible	
						Input	Output	Input	Output
	260	265	270						
1	(4)		(1)	+ 3.0	+ 60.0	0	+ 60.0	+ 20.0	+ 80.0
	240	245	250						
2	(3)		(2)	+ 0.5	+ 2.5	+ 60.0	+ 62.5	+ 80.0	+ 82.5
	235	240	245						
3				- 1.5	- 82.5	+ 62.5	- 20.0	+ 82.5	0.0
	180	185	190						
4				+ 2.5	+ 75.0	- 20.0	+ 55.0	0.0	+ 75.0
	150	155	160						
5				- 0.5	- 15.0	+ 55.0	+ 40.0	+ 75.0	+ 60.0
	120	125	130						

TABLE 5. PROBLEM TABLE FOR SAMPLE PROBLEM

necessiates a temperature adjustment which can be made in two different ways.The first method is applicable in the case of predetermined global ΔT_{min}.This global ΔT_{min} value is subtracted from the supply and target temperatures of the hot streams, yielding adjusted temperatures.These adjusted temperatures and the supply and target temperatures of the cold streams are listed and ranked in order of decreasing values.Any duplications are ignored to get the final list.The final list is shown in column 2 of Table 5. As it is indicated, this column belongs to the cold streams.For the hot streams one should add ΔT_{min} to the temperatures listed in column 2 to get column 4 of the same table.The cold and hot streams running from their supply to target temperatures are represented by arrows in the second and fourth columns respectively.The arithmetic means of the corresponding values of column 2 and 4 are listed in column 3.Every temperature in that column is known as an interval boundary temperature and is an upper and/or lower bound of an interval called a subnetwork.Generally, the following expression holds [15]

$$NSN \leq 2z-1 \qquad (11)$$

with the equality applying in cases where no two temperatures coincide.In the above expression, NSN is the number of subnetworks and z is the number of streams in the problem.With the convention introduced in Chapter I, z can be shown as follows

$$z = M+N \qquad (12)$$

The second method to adjust the temperatures is applicable in case of match dependent minimum allowed temperature. Let the hot streams to cross temperature interval boundaries at $T_b+(1/2\ \Delta T_{min})$ and cold streams to cross at $T_b-(1/2\ \Delta T_{min})$. The value of ΔT_{min} in any match is then simply the sum of the matched contributions. In problems where a global ΔT_{min} is applicable, the contributions become simply 1/2 ΔT_{min}.

The fifth column of Table 5 shows the heat capacity flow rates of the subnetworks. The values are obtained by employing the following equation.

$$Cp_i = [\underset{Hot}{\Sigma\ Cp} - \underset{Cold}{\Sigma\ Cp}]_i \qquad (13)$$

For the third interval in our example, the application of this equation results,

$$Cp_3 = [(3.0+1.5)-(2.0+4.0)] = -1.5\ kW/^\circ C\ .$$

For each subnetwork, there should be either a net heat deficit or surplus but never both. Deficit or surplus figures calculated by the following equation are listed in the sixth column.

$$\Delta H_i = Cp_i\ *(T_i - T_{i+1}) \qquad (14)$$

Again for the third interval, Equation 14 yields,

$$\Delta H_3 = -1.5*(240-185) = -82.5\ kW\ .$$

After completing interval heat balances, the next step is the heat cascading. The procedure is in two stages. First, one assumes that the heat supplied to the first subnetwork equals zero and calculates the heat flows passed on intervals by using the equation below:

$$Q_i = Q_{i-1} + \Delta H_i \qquad (15)$$

For the calculation of Q_1, Q_0 is the heat supplied to the first interval and generally denoted by Q_H.Likewise, in our example problem, Q_5 is the heat rejected to the sink utility and denoted by Q_C.

Column 7 in Table 5 shows the heat flows resulting from a value of Qh=0.Between intervals 3 and 4, the heat flow is negative (-20.0 kW), i.e., an infeasible condition.The negativity here, implies that heat flows against the natural temperature gradient or in other words, it implies that the second rule of thermodynamics is violated.To remedy this situation, an extra 20 kW of heat (i.e., the largest infeasible flow) is supplied from the external source.The resulting heat flows are all non-negative, and are shown in column 8 of Table 5.

Column 8 yields three important items of information.First, the minimum heat supply from external heat sources, necessary for feasible heat flows, is 20 kW.Second, the corresponding minimum heat load on external sinks is 60 kW.Third, there is a point in the temperature range having zero heat flow.The dark line between intervals 3 and 4 emphasizes this point at which the cold and hot streams have temperatures of 180 °C and 190 °C, respectively.From now on, this point will be called as "the pinch".

2.2.1.2 Significance of the Pinch

The causes and effects of using more than the minimum utility usage may now be discussed.Remember that, during cascading heat is supplied to the region above the pinch (hot end) and it is removed from the region below the pinch (cold end).So, it is possible to refer to hot end as a heat "sink" and the cold end as a heat "source".

First consider the effects of removing heat X kW from the sink (Figure 2.9(a)).This process necessiates the usage of extra X kW hot utility and increases the operating costs.Figure 2.9(b) shows the second possible case where X kW heat is supplied to the source.An analogous effect can be observed, this time increasing the consumption of cold utility.Finally, Figure 2.9(c) shows the effect of transferring heat across the pinch.Any heat transferred must, by enthalpy balance around the sink, be supplied from the hot utility in addition to the minimum requirement.Similarly, enthalpy balance around the source shows that the heat transfer across the pinch also increases the cold utility above the minimum required.In other words, heat transfer across the pinch incurs the double penalty of increased hot and cold utility requirement for the heat exchanger network design task.

Three principles arrived as a result of above observations suggest a general approach for the overall process-heat integration.They should always be kept in mind if the designer is to produce optimal solutions.As a summary;

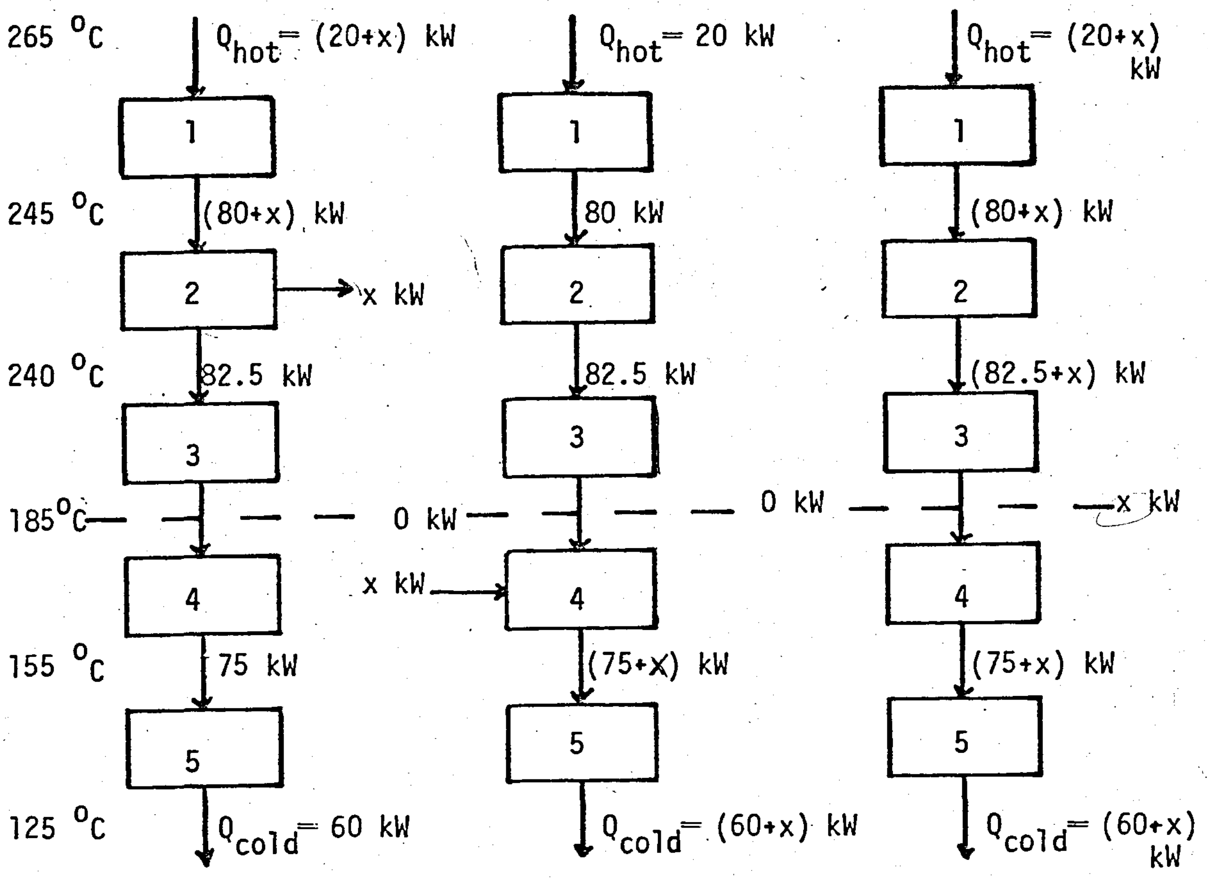


Figure 2.9- Heat transfer principles at the pinch

* Do not transfer heat across the pinch.Any heat flow across the pinch must result in the same amount of heat being added to every other heat flow in the problem in order to maintain the interval heat balances.Thus, a transfer of X units of heat across the pinch must result in increased utility requirements (Q_H and Q_C) by X units each.

* Do not use cold utility above the pinch.Above the pinch, systems having a minimized heat flow do not reject any heat.Despite this, if one chooses to reject heat into

a utility sink, he must provide the same amount of heat through utility heating.Thus, X units of cold-utility usage above the pinch result in X additional units of hot-utility usage.

* Do not use utility heating below the pinch.Below the pinch, systems having a minimized heat flow do not absorb any heat.Any heat supply through utility heating, X, must therefore lead to a cold-utility requirement of X, over and above the minimum necessary.

2.2.1.3 The Pinch in the Grid Representation

The heat exchanger network from the flowsheet in Figure 2.10(a) [4] can be represented in the grid form introduced by Linnhoff and Flower [15] ; see Figure 2.10(b).The advantage of this representation is that the heat exchange matches 1 and 2 (each represented by two circles joined by a vertical line in the grid) can be placed in either order without redrawing the stream system.In the flowsheet representation, if it were desired to match recycle against the hottest part of the reactor effluent, the stream layout would have to be redrawn.Also, the grid represents the countercurrent nature of the heat exchange, making it easier to check exchanger temperature feasibility.Finally, the pinch is easily represented in the grid, whereas it cannot be represented on the flowsheet.

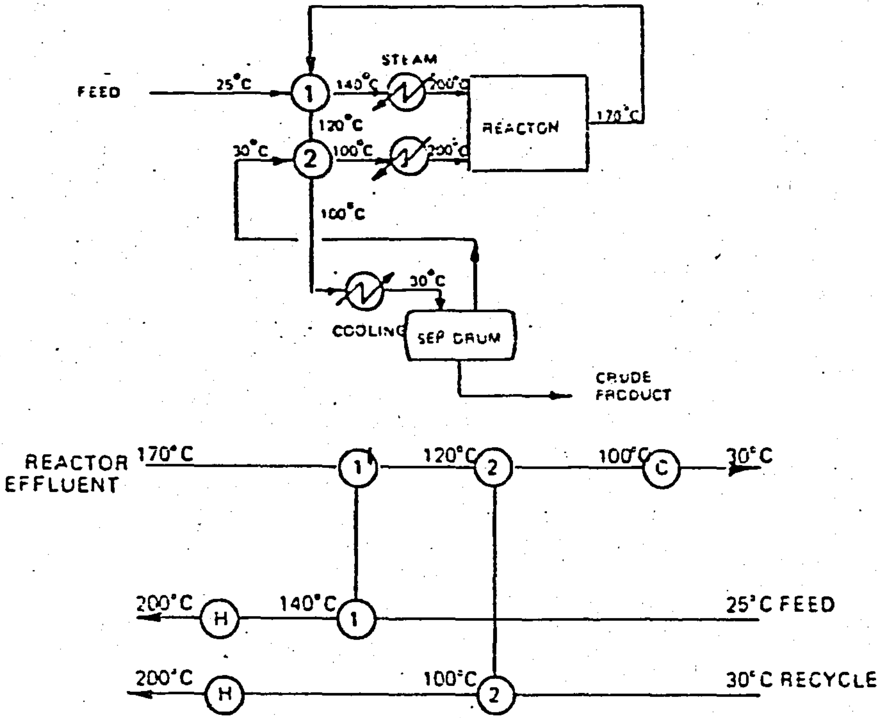


Figure 2.10- A flowsheet and its grid representation [4]

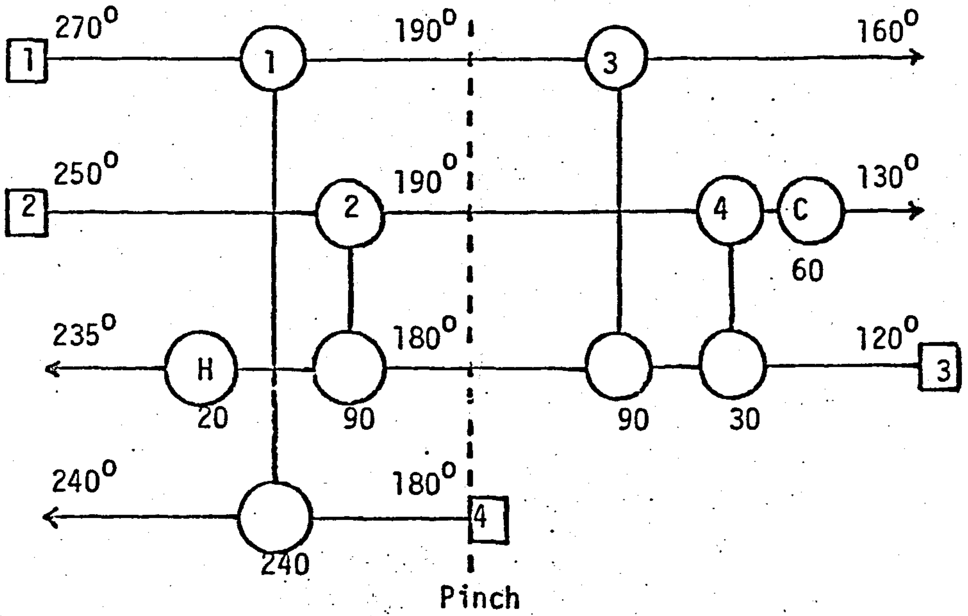


Figure 2.11- Grid representation of the sample problem

The grid representation developed for the sample problem is illustrated in Figure 2.11. Notice that stream number four starts at the pinch. In fact in problems where the streams all have constant CP's, the pinch is always caused by the entry of a stream, either hot or cold.

2.2.1.4 Factors Affecting the Occurence of Pinches

As mentioned earlier in Chapter I, a pinch does not occur in all heat exchanger network problems.Certain problems remain free of a pinch until the minimum allowed driving force, ΔT_{min} is increased up to or beyond a treshold value ΔT_{tresh}. In other words, from $\Delta T_{min} = 0$ to $\Delta T_{min} = \Delta T_{tresh}$, the need for a utility (hot or cold, but not both) is invariant, and thereafter the need for the second utility appears and both utilities increase in parallel showing the typical characteristics of a pinched problem.

It is interesting to note that virtually all early research work in design was focused -by accident- on treshold problems. Linnhoff and Hindmarsh [25] conclude that this explains why none of the early work in heat exchanger network design generated much impact in industrial practice. Actually, treshold problems are rarely encountered in industry. Following discussion gives the reasons of this.

In applying the problem table procedure to the sample problem it was assumed that the utilities were available at extreme temperatures, i.e. the hot utility was hot enough and the cold utility cold enough for all process requirements.In practice, this is rarerly desirable as less extreme utilities tend to cost less, i.e.low pressure steam for process heating costs less than high pressure steam, cooling water costs less than refrigeration, etc.There is often a good cost incentive for reducing extreme temperature utility loads by the introduction of intermediate temperature utilities.The reasoning in "significance of the pinch", tells us that any new hot utility must be supplied above the pinch and any new cold utility must be supplied below the pinch.Failure to do so would incur the double penalty of increased utility heating and cooling.

In Figure 2.12(a), a new hot utility supply has been introduced to the hot end of a hypothetical problem.As the heat load on this new utility increases, savings are made on the hottest utility supply (see Figure 2.12(b)). There comes a point when the hottest utility load is reduced to such an extent that it just satisfies the heating requirements in the hottest region of the problem (see Figure 2.12(c)). The result is a division of the hot end of the heat exchanger network design task into two separate regions, i.e. a new pinch has been created. As it is a direct consequence of the introduction of the new utility, it is called a utility pinch. The problem table algorithm is easily adapted to calculate the maximum loads on intermediate temperature utilities and the resulting utility pinch locations.

With this understanding it is hardly surprising to find that, in industrial heat exchanger network design,

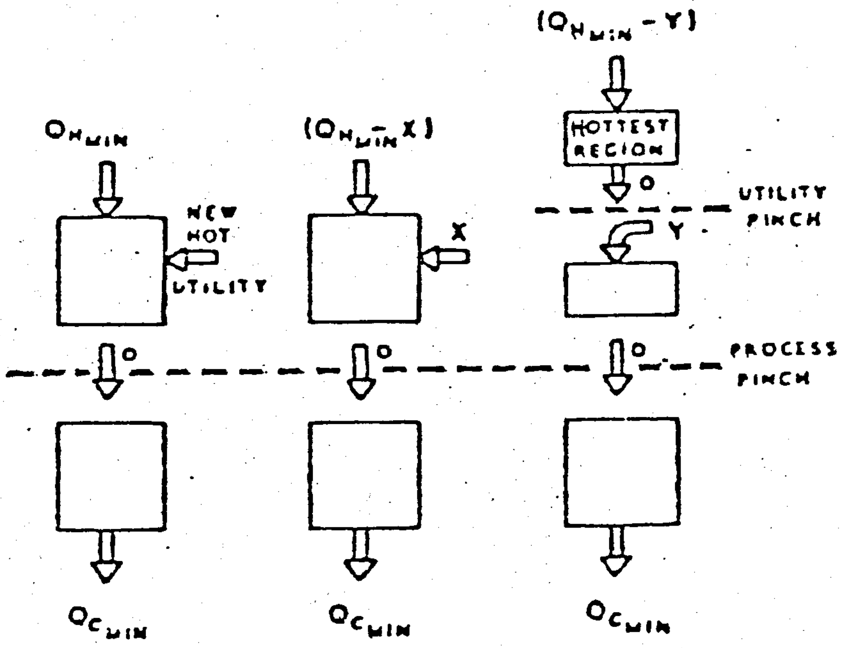


Figure 2.12- Formation of a utility pinch [25]

the occurance of an unpinched or treshold problem is extremely rare.The pinched problem is the norm.

2.2.1.5 Capital Cost Implications of the Pinch

Before discussing the capital cost implications of the pinch, it will be helpful to remind the "minimum number of units" targeting equation given previously in section 2.1.2.1.

$$u_{min} = N-1 \qquad (7)$$

Application of this equation to the hot and cold ends of the sample problem leads four and three units respectively, making a total of seven units to complete the design.Note that by accepting the pinch division, stream Nos. 1, 2 and 3 are counted twice by the targeting equation.They exist in both the hot and cold ends. Now, apply the targeting equation singularly to the whole problem.Stream Nos. 1, 2 and 3 are no longer counted twice and the target for the minimum number of units to complete the design is five.Under such conditions to achieve a five unit design means that either:

- "X" amount of heat must be transferred across the pinch, incurring the double penalty of increased hot and cold utility usage or

- the ΔT_{min} constraint initially imposed can be relaxed in certain exchangers subject to $\Delta T_{min} > 0$.

In the first case there is a cost trade-off between the number of capital items and the utility usage.In the second case there is a cost trade-off between the number of units and surface area.The exploration of these trade-offs is fully discussed in section 2.2.4.

2.2.2 Data Analysis

As it is indicated earlier, data analysis is the first step in the application of Pinch Technique.It yields the targets:

i) Minimum utility consumption.
ii) Minimum number of heat exchanger units.
iii) Minimum heat transfer area.

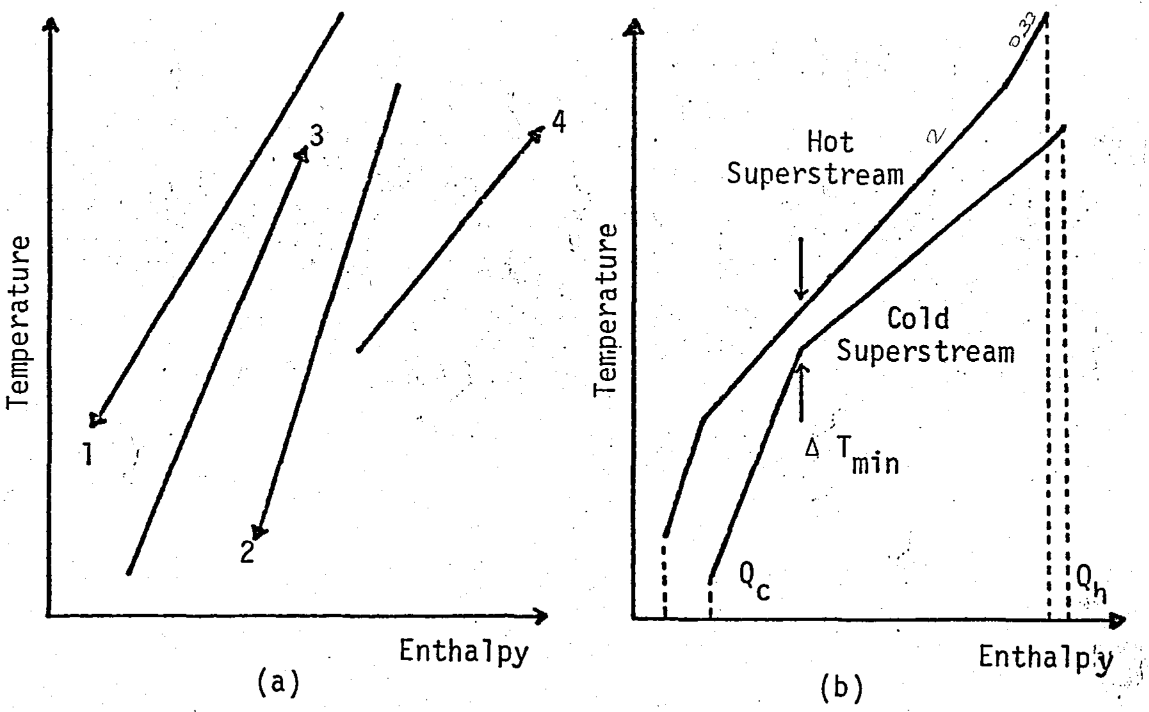


Figure 2.13- Construction of composite curves for the sample problem

Determination of the first two targets is explained in related sections and will not be discussed any further. The third target, namely determination of minimum heat transfer area is in fact not important from this technique's point of view. Linnhoff and Hindmarsh [25] explain that widely differing solutions for the same problem generally feature similar overall surface areas as long as their degree of energy recovery is similar. From this standpoint what is important in the early stage of network design is to generate networks satisfying the first and the second targets since the heat transfer area is fixed within a few percent by one's specifying the utility usage for the network.

Since temperature/enthalpy diagrams are used for the determination of minimum heat transfer area, it was considered to be useful to explain the construction of these diagrams priorly.The data of the sample problem (see Table 4) will be used for this purpose.

In Figure 2.13(a) two hot streams - represented by the lines with the arrow heads pointing to the left - and two cold streams - represented by the lines with the arrow heads pointing to the right - are plotted separately.Here, an important property of T/H diagrams should be remembered; since we are only interested in enthalpy changes of streams, a given stream can be plotted anywhere on the enthalpy axis.Provided it has the same slope and runs between the same supply and target temperatures, then wherever it is drawn on the H-axis, it represents the same stream.

With CP assumed constant, for a stream requiring heating from a supply to a target temperature, the total heat added will be equal to the stream enthalpy change, i.e.

$$Q = \int_{T_s}^{T_t} CP\, dT \qquad (\ 2'\ )$$

For a stream requiring cooling from a supply (T_s)to a target temperature (T_t), this equation is applicable with the correction (T_s-T_t) which is necessary since $T_s > T_t$ in case of hot streams.The slope of the line representing the stream (hot or cold) "i" is,

$$dT/dQ= 1/CP_i \qquad (\ 16\ )$$

Temperature values at which the slope of a composite curve changes are known as "corner points".

Furnished with the information given above, it is now possible to construct T/H diagram of the sample problem.The hot streams, with their supply and target temperatures define a series of interval temperatures 270 to 130 °C. Between 270 and 250 °C, only stream 1 exists, and so the heat available in this interval is given by CP_1(270-250). However between 250 and 160 °C, both of the hot streams exist and so the heat available in this interval is (CP_1+CP_2) (250-160).Between 160 and 130 °C, only stream 2 exists, with a heat load of CP_2(160-130).The series of values of H for each interval can be obtained in this way, and the result re-plotted against the temperature intervals.The resulting T/H plot is a single curve representing all hot streams.A similar procedure gives the composite of the cold streams in the sample problem.Both composite curves are shown in Figure 2.13(b).The overlap between these curves represents the maximum amount of heat recovery possible within the process.The over-shoot of the hot composite represents the minimum amount of external cooling required and the overshoot of the cold composite represents the minimum amount of external heating.Becouse of the kinked nature of the curves, they approach most closely at one point.This is the pinch point which is located earlier by an analytical procedure called problem table method.If one sets the vertical distance between the hot and cold composites at pinch point to ΔT_{min}, he can read the Q_h and Q_c values on the H axis of T/H diagram. For the sample problem, with a given ΔT_{min} of 10 °C, the dashed lines in Figure 2.13(b) project these requirements on H axis.

Having completed the construction of composite curves, the next step is to divide up these curves into simple countercurrent sections. The procedure is to draw lines from the corner points lying on the hot composite in downwards direction and to draw lines from the corner points lying on the cold composite in upwards direction. For each section obtained, we have a hot superstream formed by one or more hot process streams and a cold superstream formed by one or more cold process streams. Heat contents of these superstreams and log-mean temperature difference for each section can be computed. To minimize the overall heat transfer area, the stream matches should be done "vertically" between the composite curves since only this arrangement is equivalent to pure countercurrent flow in a single heat exchanger. In Figure 2.14, section ABCD shows the vertical matches. Any match away from the vertical (e.g., section CDEF) will gain the local advantage of a larger ΔT. However, it will later require a match in the opposite direction (with a smaller ΔT). The net effect of such "criss-crossing" is an increase in the area requirement.

For a system in which heat transfer coefficients are uniform, the assumption of vertical stream matching leads to rigorous minimum area. By applying the conventional

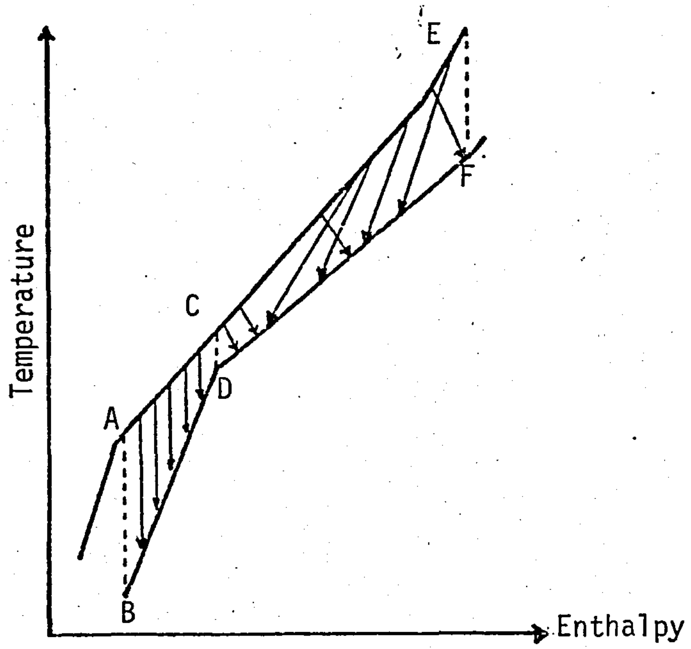


Figure 2.14-Criss-crossing matchups between the composite curves

heat transfer equation $Q = U.A. \;\Delta T_{LM}$ to each section, a total area is obtained. For nonuniform heat transfer coefficients, the vertical model is a simplification. However, a useful numerical approximation that applies to this situation is given by Towsend and Linnhoff [27]:

$$A_{target} = \sum_{i} \frac{1}{\Delta T_{LMi}} \left[\sum_{j} \left[\frac{q_j}{h_j} \right] \right]_i \qquad (17)$$

where, in section i, there are j streams (hot and cold) with their individual heat loads, q_j, and their respective stream "film and fouling" coefficient, h_j. ΔT_{LM} is the log-mean temperature difference in section i. As it is indicated in [27], this equation provides a useful estimate of minimum overall heat exchange area with the accuracy within 10 per cent.

After the determination of target (iii), the data analysis step is completed.The following task is to perform the design of a network that can reach the targets mentioned above.

2.2.3 Network Design

In this section, the discussion begins with the philosophy of the method and is followed by details of the actual procedure, namely the development of "feasibility criteria" which quantify the restrictions placed on design by the pinch, the use of a "tick-off heuristic" to ensure the design is steered towards the fewest possible units and the solution of the "remaining problem" allowing consideration of process constraints and other requirements.

2.2.3.1 The Philosophy

The pinch represents the most constrained region of a design; after all, ΔT_{min} exists between all hot and cold streams at the pinch.As a result the number of feasible matches in this region is severely restricted.Quite often there is a crucial or "essential" match.If this match is not made, this will result in heat transfer across the pinch and thus in increased hot and cold utility usage.The pinch design method,therefore

- recognises the pinch division
- starts the design at the pinch developing it separetely into two remaining problems.

This approach is completely different from the normal intuitive approach of starting the design at the hot side and developing it towards the cold.When a design is started at the hot side, initial design decisions may later necessitate follow-up decisions which violate the pinch.On the other hand, when a design is started at the pinch, initial design decisions are made in the most constrained part of the problem are less likely to lead to difficulties later.

Thus, commencing a design at the pinch has the distinct advantage of allowing the designer to identify essential matches or topology options in the most constrained region of the design which are in keeping with minimum utility usage.There is a further advantage, namely the designer will always have the option to violate the pinch if required with full knowledge of the final penalties to be incurred.When a match is placed knowingly in violation of the pinch the heat flow across the pinch can quickly be established.This heat flow is equivalent to the final increase in hot and cold utility.

Once away from the pinch the design task is no longer so constrained hence the number of topology options usually increases.This increase in the number of options can be used to advantage by the designer.After all, the design objective is not just the identification of a cost optimal topology but also one which is safe and controllable.By discriminating between match options the designer can steer his design, using his judgement and process knowledge, towards a safe, controllable and practical network.

In developing the pinch design method this benefit has been recognised.As a result, the method does not "tell" the designer which matches to make but rather it informs him of his options.In the temperature constrained region near the pinch essential matches are identified using feasibility criteria.The same criteria will inform the designer whether there are options available at the pinch and whether stream splitting is required.When designing away from the pinch the need for feasibility criteria diminishes and the method allows the designer to choose topologies based on process requirements.

2.2.3.2 Feasibility Criteria at the Pinch

The identification of essential matches at the pinch, of available design options and the need to split streams, is achieved by applying three feasibility criteria to the stream data at the pinch.Here, the introduction of a new term is necessary since in developing these criteria, reference is made to a special type of exchangers."Pinch exchangers" (sometimes called "pinch matches") are the ones which have the minimum temperature approach, ΔT_{min}, on at least one side and at the pinch. According to this definition and also keeping the principles given in sub-section 2.2.1.2 in mind, one may conclude that a pinch match is the process interchanger which brings a stream to its pinch temperature. As long as utility cooling is not allowed above the pinch, hot streams should be brought to pinch temperature by this type of exchangers. In case of "below the pinch design", utility heating is not allowed and cold streams should be brought to pinch temperature by pinch exchangers. Back to Figure 2.11, the exchangers that fit into this definition are Nos. 1 and 2 for the hot end, and 3 for the cold end. Note that exchanger number 4 is not a pinch match.

2.2.3.2.1 The Number of Process Streams and Branches

The first feasibility criterion concerns the stream population at the pinch. The population of hot and cold streams has to be such that it will allow an arrangement of exchangers compatible with minimum utility usage.

Consider a hot end design as in Figure 2.15(a). Utility cooling above the pinch would violate the minimum utility objective. Therefore, each hot stream has to be cooled to the pinch temperature by process exchange. This is attempted in Figure 2.15(a) by placing pinch matches between hot stream No.2 and cold stream No.5 and hot stream No.3 and cold stream No.4. Notice,

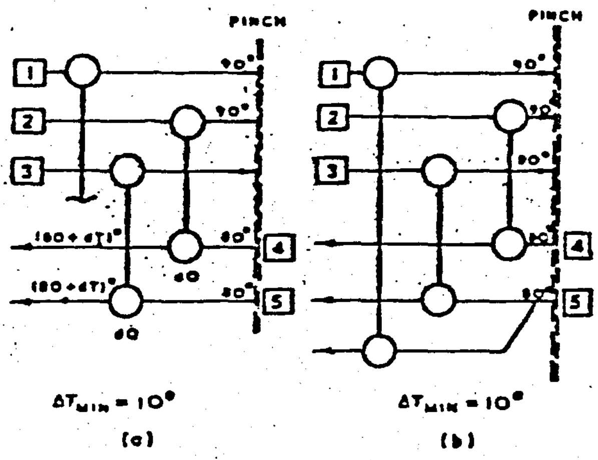


Figure 2.15-(a) An infeasible hot end design at the pinch
(b) Stream splitting at the pinch [25]

however, that having made these matches hot stream No.1 cannot be matched with either cold stream without violating the ΔT_{min} constraint! Utility cooling would now be required above the pinch to cool stream No.1 to the pinch temperature.Under such circumstances, it is said that the original stream data at the pinch is not compatible with a minimum utility design.

When this incompatibility occurs the streams at the pinch need "correcting" by stream splitting (see Figure 2.15(b)). By splitting a cold stream an extra cold "branch" is created, allowing a pinch match with hot stream No.1.

To summarise, the hot end stream population at the pinch is compatible with a minimum utility design only if a pinch match can be found for each hot stream.For this to occur the following inequality must apply

$$NH \leq NC. \qquad (18\text{-a})$$

where NH is the number of hot streams or branches and NC is the number of cold streams or branches.Stream splitting may be needed to ensure that the inequality is fulfilled.

The converse arguments apply below the pinch.To avoid utility heating each cold stream must be brought to pinch temperature by process exchange, see Figure 2.16.As a result, a pinch match is required for each cold stream at the pinch and this is possible only if inequality given below holds

$$NH \geq NC. \qquad (\ 18\text{-b}\ )$$

Once again stream splitting may be necessary to ensure that inequality is fulfilled.

2.2.3.2.2 The CP Inequality for Individual Matches

The second feasibility criterion is concerned with temperature feasibility.As shown in Figure 2.17, temperature driving force in a pinch match cannot decrease away from the pinch.For this condition to be fulfilled the following CP inequalities must apply in every pinch match.For a hot end pinch match,

$$CPH \leq CPC \qquad (\ 19\text{-a}\ )$$

and for a cold end pinch match,

$$CPH \geq CPC \qquad (\ 19\text{-b}\ )$$

where CPH is the heat capacity flowrate of a hot stream or stream branch and CPC is the heat capacity flowrate of a cold stream or stream branch.

To illustrate the validity of this criterion,

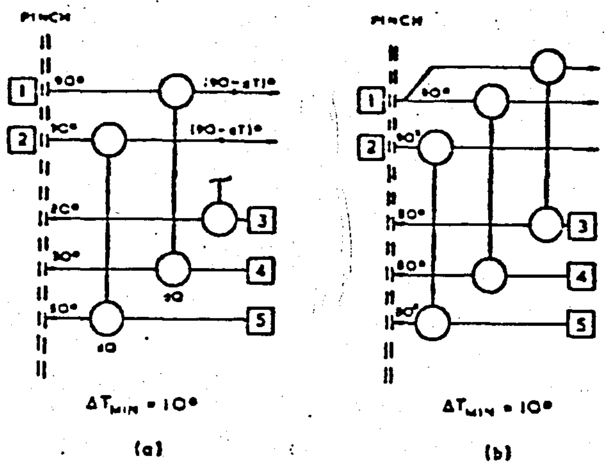


Figure 2.16-(a)An infeasible cold end design at the pinch
(b) Stream splitting at the pinch [25]

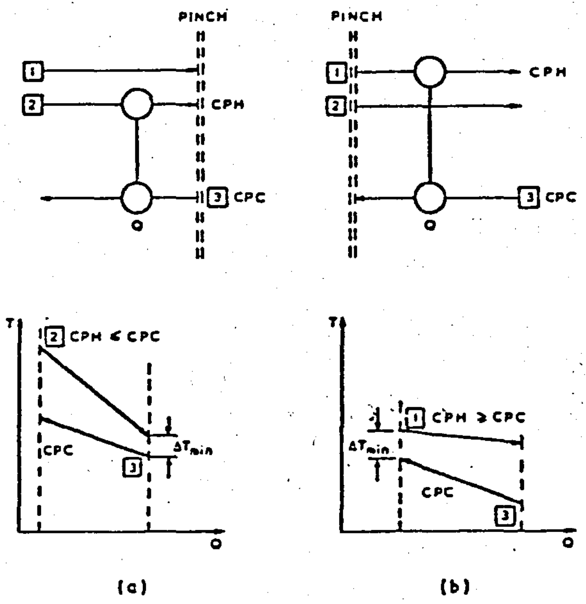


Figure 2.17-(a)A feasible pinch exchanger above the pinch
(b) A feasible pinch exchanger below the pinch [25]

consider Figure 2.11 and assume that stream No. 1 is matched to stream No. 3 above the pinch point.Applying "tick-off" rule to that match results an exchanger with a heat load of 110 kW.

By simple heat balance, the inlet temperature of stream No. 1 to the exchanger is found to be 226.7 °C which is completely infeasible.For a feasible match, it should have been greater than or at least equal to 245 °C. It is clear that the reason of this infeasibility is the violation of inequality 19-a.

If an arrangement of matches fulfilling these inequalities is not possible then it is necessary to change one or more CPs by stream splitting.

It should be noted that inequalities given above only apply at the pinch.Away from the pinch, temperature driving forces may have increased sufficiently to allow matches in which the CPs of the streams matched violate the inequalities.

2.2.3.2.3 The CP Difference

To understand the third feasibility criterion at the pinch it is convenient to define the "CP difference".For a hot end pinch match,

$$\text{CP difference} = CPC - CPH \qquad (20\text{-a})$$

and for a cold end pinch match,

$$\text{CP difference} = CPH - CPC. \qquad (20\text{-b})$$

Similar equations can be written for differences in the overall sum of hot stream CPs and cold stream CPs at the pinch.Immediately above the pinch,

$$\text{Overall CP difference} = \sum_{1}^{NC} CPC - \sum_{1}^{NH} CPH \qquad (21\text{-a})$$

and immediately below the pinch,

$$\text{Overall CP difference} = \sum_{1}^{NH} CPH - \sum_{1}^{NC} CPC \qquad (21\text{-b})$$

Figure 2.18 illustrates how the concept of the CP difference for an early identification of matches that are feasible themselves but are not compatible with a feasible overall network. In Figure 2.18(a), a case is shown where the sum of the match CP differences equals the overall difference. All streams at the pinch are involved in pinch exchangers. Figure 2.18(b) shows a hot end pinch design for a different problem where the pinch match CP differences amount to less than the total. In this case not all streams at the pinch are involved in pinch matches. Figure 2.18(c) shows a different problem

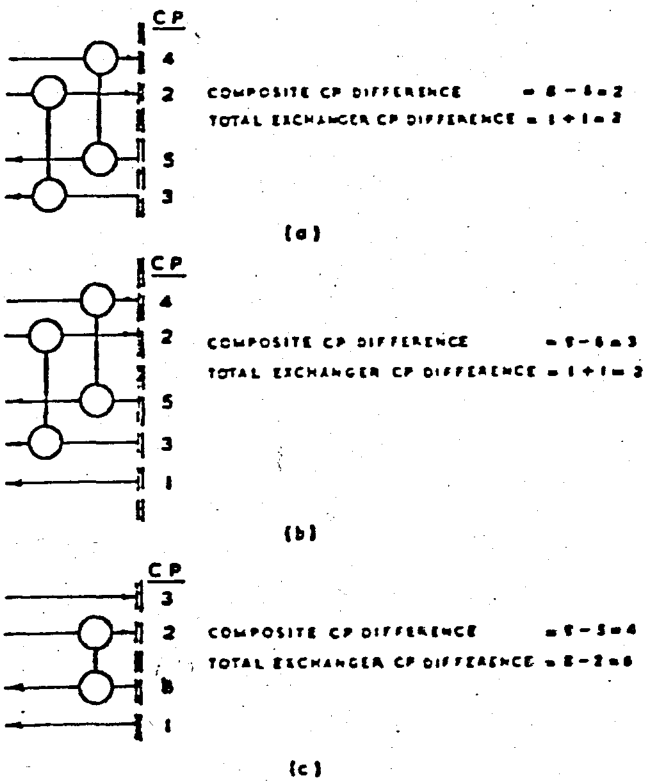


Figure 2.18- (a) Two feasible pinch topologies showing that composite CP (b) Difference bounds the total exchanger difference (c)An infeasible match based on the CP difference [25]

again where the pinch match CP difference exceeds the total.The pinch match shown is feasible by itself since it fulfills inequality 19-a but it is incompatible with the overall CP difference.The pinch match has a CP difference of six units whereas the total available is only four.Thus, it will not be possible to complete this design.A match between the remaining hot stream and the remaining cold stream, which is required to cool the hot stream to the pinch temperature, is not feasible.We can generalise by saying that the CP differences of all pinch matches must always be bounded by the overall CP difference.

2.2.3.2.4 Applications of Feasibility Criteria (Design at the Pinch)

The solution developed for the sample problem (Figure 2.11) does not necessitate any special effort since there are enough options for the designer to fulfill the feasibility criteria.However, in practice, more complex cases may be encountered requiring stream splitting.

Consider Figure 2.19(a), which shows an above-the-pinch stream set.The population criterion is met, but after the hot stream of CP= 7.0 is matched against the only cold stream large enough (CP= 12.0), the remaining hot stream of CP= 3.0 cannot be matched against the remaining cold stream of CP= 2.0.If a hot stream were now to be split, the number count criterion would not then be

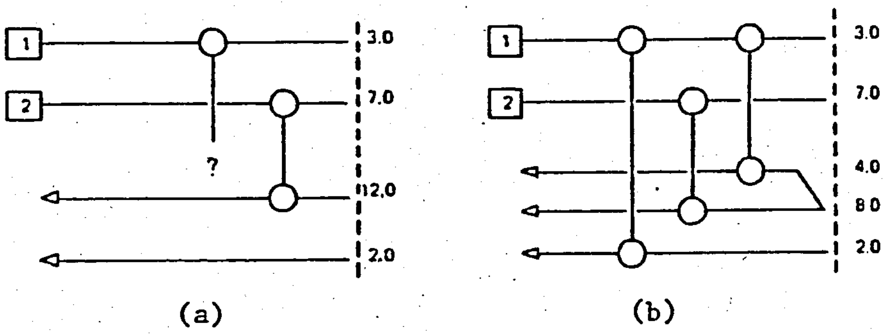


Figure 2.19- Applications of feasibility criteria [4]

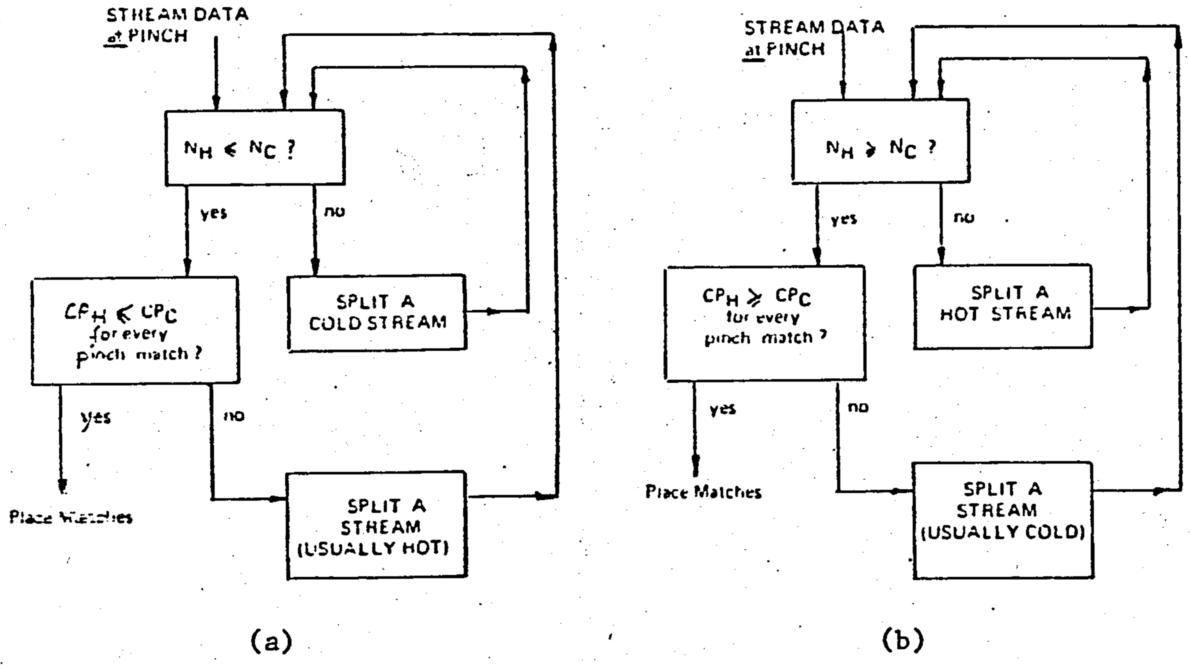


Figure 2.20- Algorithms for design at the pinch (a) Hot end design (b) Cold end design [4]

satisfied and a cold stream would then have to be split as well! It is better to split the large cold stream from the outset as shown in Figure 2.19(b), producing a solution with only one split.Step-by-step procedures for finding stream splits are given for above and below the pinch in Figures 2.20(a) and (b) respectively.Note that the below-the-pinch criteria are the "mirror image" of those for above the pinch.

Another important aspect of stream splitting at the pinch will, now be illustrated by an example problem.The stream data are shown in Figure 2.21(a) and the CP data are listed in Figure 2.21(b) in what is called the "CP-table".Hot stream CPs are listed in the column on the left and cold stream CPs in the column on the right and the relevant CP criterion noted in the box over the table.There are two possible ways of putting in the two required pinch matches, shown at the top of Figure 2.21 (c).In both of these, the match with the hot stream of CP= 5.0 is infeasible, hence we must split this stream into branches CP= X and CP= (5.0-X) as shown in the bottom table in Figure 2.21(c).Now, CP_H= X or (5.0-X) can be matched with CP_C= 4.0, as shown.However, one of the split branches has no partner, i.e. the number count criterion has failed and a cold stream must be split.Either CP_C= 4.0 or CP_C= 3.0 could be split, and Figure 2.22(a) shows CP_C= 3.0 split into branches Y and (3.0-Y).To find initial values of X and Y it is recommended that all matches except for one are set for CP equality.Thus in Figure 2.22(b), X is set equal to 4.0 and Y set equal to 1.0, leaving all the available net CP difference concentrated in one match.The procedure quickly identifies a set of feasible limiting values.Starting from this set, it is then easy to redistribute the available CP difference amongst the chain of matches, for example as shown in Figure

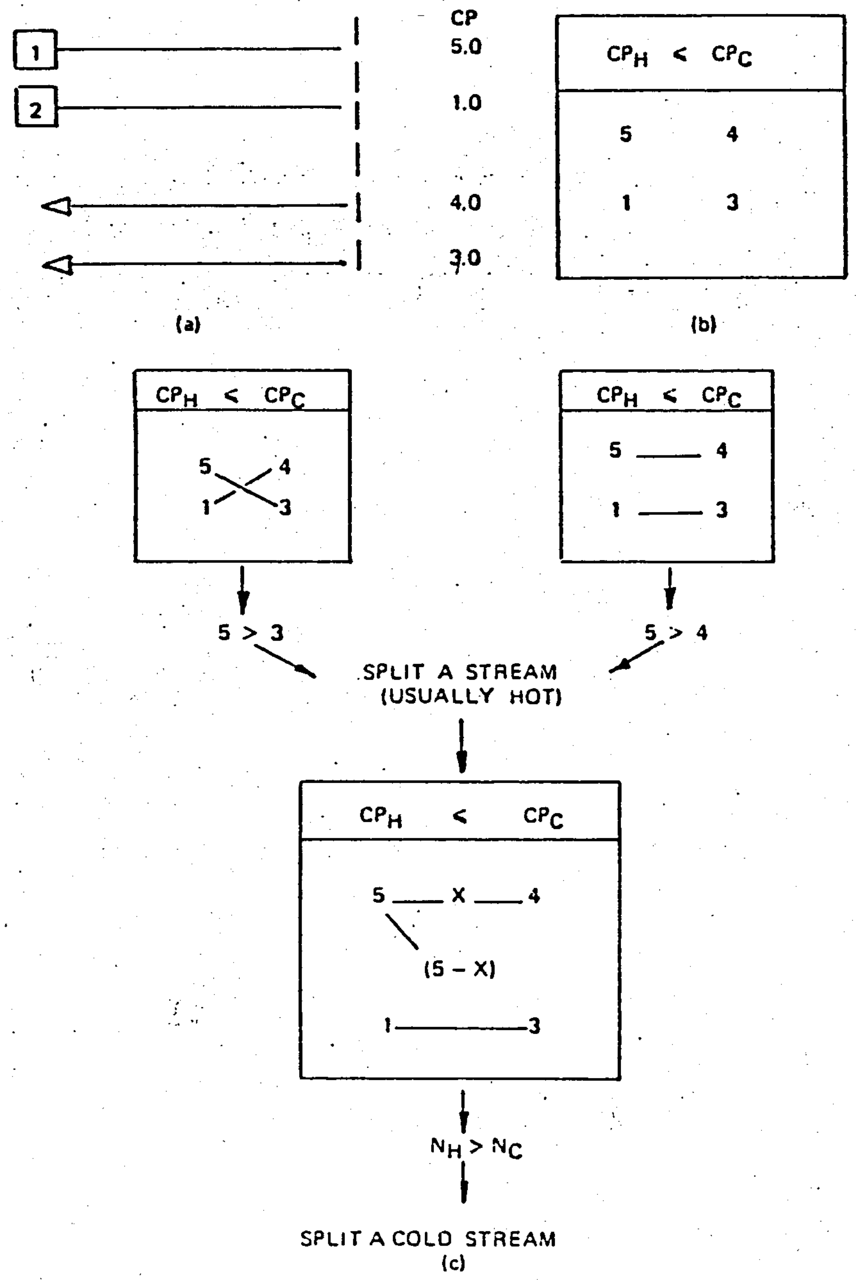


Figure 2.21- Use of CP-table [4]

2.22(c).This design is shown in the grid in Figure 2.22(d).The way in which the branch CPs are distributed is often dictated by the loads required on individual matches by the "ticking-off" rule.

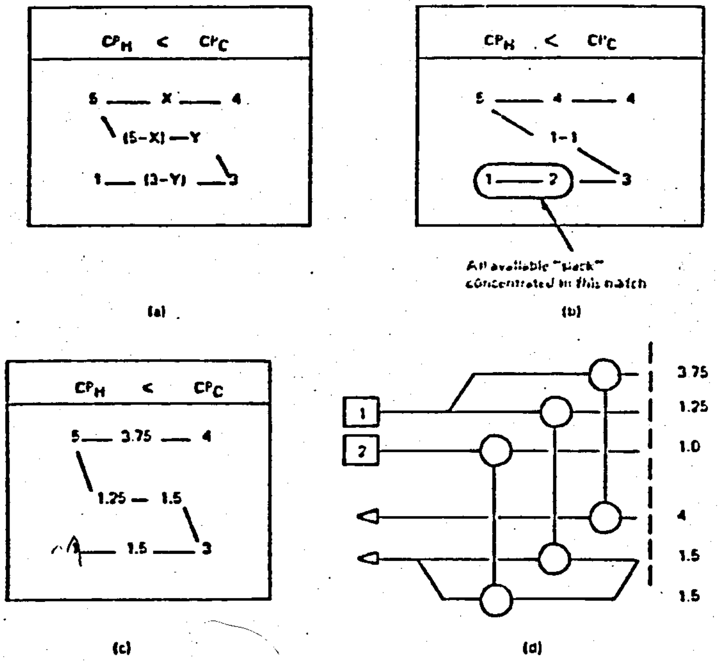


Figure 2.22- Determination of split branch flows [4]

2.2.3.3 The "Tick-off" Heuristic

Once a pinch topology has been chosen, the design of both hot and cold ends must be continued in such a manner as to keep capital costs at minimum, i.e. the final designs ought to be steered towards the minimum number of units. This can be achieved by employing a "tick-off" heuristic to identify the heat loads on the pinch exchangers.

The heuristic results directly from the targeting equation for the minimum number of units (see Equation 7). This equation is satisfied if every match brings one stream to its target temperature or exhausts a utility. In this case, the match is said to "tick-off" the stream or utility, i.e. the stream or utility need no longer be considered part of the remaining design task.

The pinch exchangers can usually be made to tick-off streams by choosing each exchanger load to equal the smaller heat load of the two streams matched.The CP inequalities 19-a and 19-b will guarantee the possibility of choosing pinch exchanger loads by ticking-off streams as long as the stream CP remains constant with varying temperature and as long as cold and hot stream temperature overlaps do not require an excessive number of shells for a single pinch match.

The tick-off heuristic is a "heuristic" as it can occasionally penalise the design by introducing the need for increased utility usage.Temperature driving force, essential elsewhere, may be used up excessively in pinch exchangers that are extended too far into the remaining problem.In such cases the designer can choose either to

* reduce the load on the offending pinch match and run the risk of needing more than the minimum number of units

* use another pinch topology in which the tick-off heuristic does not cause essential driving force to be used up.

The problem table algorithm can be used to check whether a maximised pinch match load is in keeping with minimum utility usage.Consider, for example, a hot end design.Application of the problem table algorithm to the complete hot end would tell us that utility heating would be required and no utility cooling, i.e. the hot end effectively constitutes a treshold problem where the ΔT_{min} specified is the treshold value. Now consider the situation where a pinch match has been identified and its load has been determined using the tick-off heuristic.There will exist a "remaining problem" of hot and cold streams (strictly speaking parts of streams) for which a network design is required.The problem table algorithm can be applied to this remaining problem.One of two results would then occur.

First,the algorithm may calculate that no utility cooling is required to solve the remaining problem and the utility heating predicted would be the same as before.In this case the designer knows that the pinch match load he has assigned, using the tick-off heuristic, will not penalise the design in terms of increased utility usage.

Second, the algorithm may calculate that utility cooling is required for the remaining hot end problem and that the hot utility usage would, accordingly, be increased.In this case the designer knows that the pinch match load he has assigned, using the tick-off heuristic, is not compatible with minimum utility usage.

The above technique has been called remaining problem analysis [4] for obvious reasons.It is a dependable mechanism to check the consequences of the application of the tick-off heuristic.However, due to the effort involved it should only be used in complex situations to confirm key design steps.

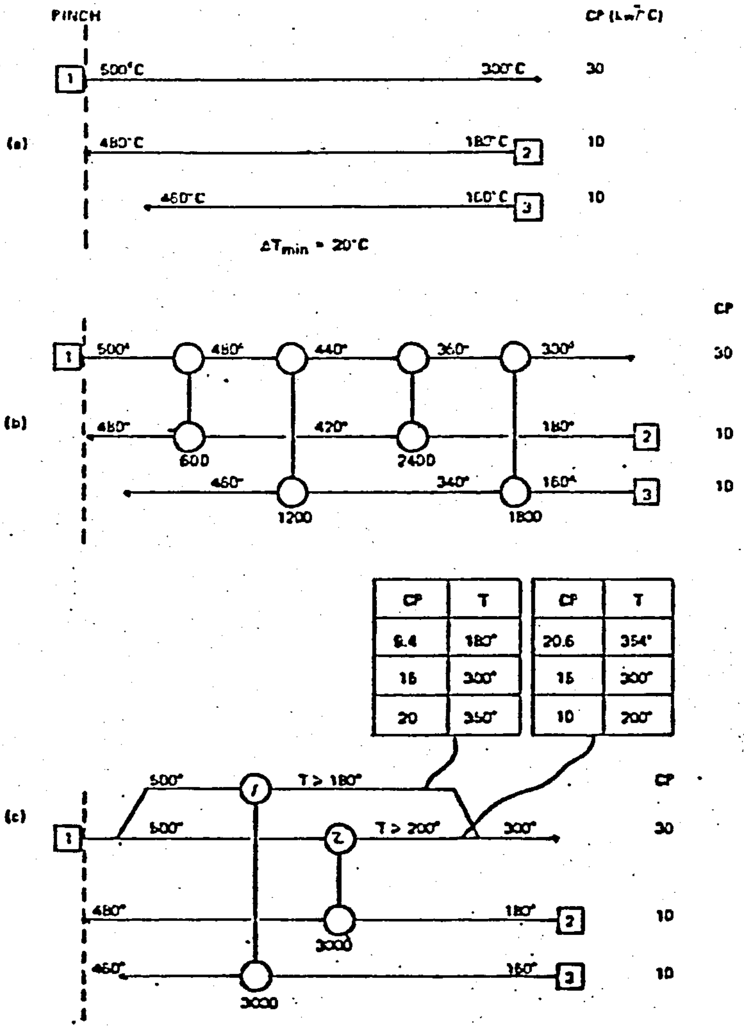


Figure 2.23- Design away from the pinch [4]

2.2.3.4 The Remaining Problem (Design away from the Pinch)

In accordance with the pinch design method philosophy the designer is given a "free hand" once the temperature driving forces no longer restrict topology options.

Thus when designing away from the pinch in the "remaining problem" matches are chosen discrimately by the designer to satisfy the process objectives.For example, heaters and coolers can be placed for direct control of stream target temperatures.Preferred topology requirements or materials, safety and other constraints can be used to steer the placement of other matches.

In addition, the remaining problem analysis technique discussed in sub-section 2.2.3.3 is not only restricted for checking the placement of pinch matches.It can also be used to ensure that matches placed in the remaining problem are compatible with the minimum utility objective.

However, in many problems it is not possible to reach the optimal solution though feasibility criteria at the pinch are fulfilled.An example will be given here to illustrate one of the problems which can be encountered during design, away from the pinch.

Consider the problem given in grid representation in Figure 2.23(a).Analysis of stream data shows a pinch at the supply temperature of stream No. 1 and the target temperature of stream No. 2 and hot and cold utility requirements both of zero.The design problem is therefore entirely "below the pinch", with only one pinch match is possible, i.e. that between streams 1 and 2.

This is a feasible match ($CP_1 > CP_2$), and if its load is maximised to tick off stream 2 (a load of 3000 kW), stream 1 is cooled to 400 °C.Here, the problem arises: stream 1 is no more hot enough to bring stream 3 up to its target temperature of 460 °C.Since, heating below the pinch is not allowed for a maximum energy recovery solution, the design step of ticking off stream 2 would lead to a design that failed to reach the energy target.An alternative strategy is shown in Figure 2.23(b).The load on the pinch match is limited to 600 kW so that stream 1 remains just hot enough (at 480 °C) to bring stream 3 up to its target temperature.However, the next match (between streams 1 and 3) also cannot be maximised in load, because now stream 2 has to be brought up to 420 °C by stream 1.The load on the second match between streams 1 and 2 has to be limited, allowing a final match (between streams 1 and 3) to finish the design.The phenomenon of stream temperatures and CPs causing repeated matching of the same pair of streams is known as "cyclic matching".

Cyclic matching always leads to structures containing loops (see sub-section 2.1.2.1) and hence more than the minimum number of units.The only way to avoid cyclic matching is to employ stream splitting away from the pinch.In Figure 2.23(c) the heavy stream, stream 1, is split into two parallel branches, and each branch matched separately to a cold stream.The two matches can now be maximised to tick off the two cold streams without running into temperature problems. A u_{min} design results. Notice also that the stream split design gives an element of flexibility to the network. The split stream branch flowrates can be chosen within limits dictated by the cold stream supply temperatures. Thus if the branch matched against stream 3 is cooled to 180 °C (the minimum allowed) it will have a CP of 9.4 and by mass balance the CP of the other branch will be 20.6. A CP of 20.6 in the branch matched against stream 2 leads to an outlet temperature on this branch of 354 °C which is much higher than the minimum allowed.The same argument can be applied to define the other set of limits based on stream 2 supply temperature.The branch matched against stream 2 then has a CP of 20 and an outlet temperature of 350 °C.The CP of the branch matched against stream 3 may therefore vary between 9.4 and 20 with the parallel limits on the other branch being 20.6 and 10.These results are summarised in Figure 2.23(c), along with the results for equal branch flows.This type of flexibility is normally available in stream split designs and can be very useful.

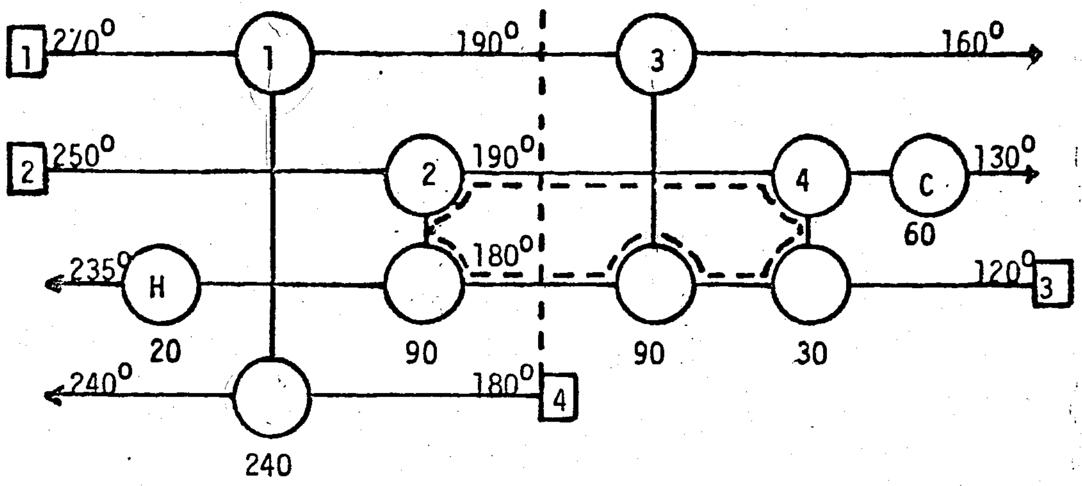
2.2.4 Simplifying the Minimum Utility Design (Energy Relaxation)

There is generally a scope to simplify minimum utility designs by a controlled reduction in the number of units.By transferring heat across the pinch and therefore increasing the utility usage the number of capital items can be reduced.There is a trade-off between units (capital cost) and the utility usage (energy cost).In order to explore the scope for a controlled reduction in the number of units it is important to understand the concepts of heat load loops and heat load paths.

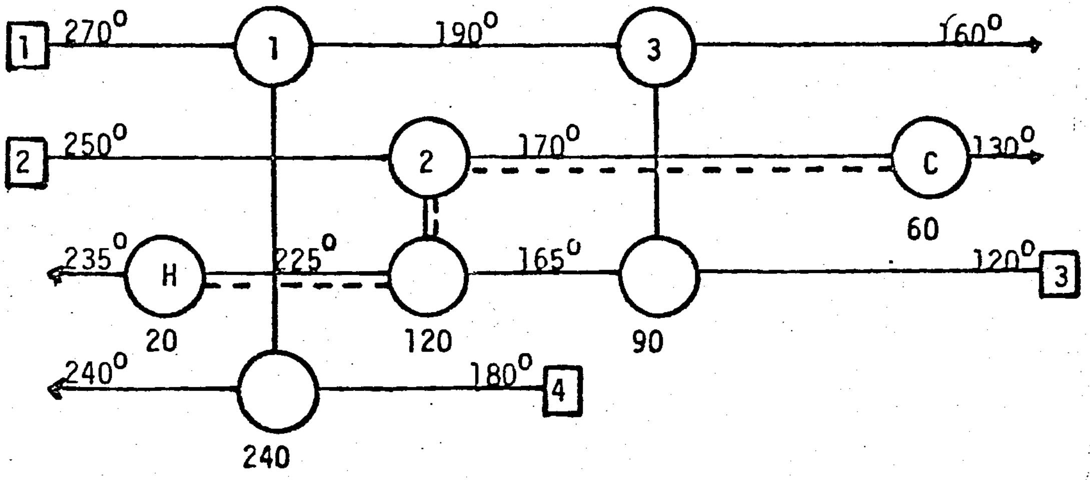
Whenever a design features more than the target minimum number of units for the whole problem, ignoring the pinch, it is due to the existence of heat load loops.This situation is illustrated by an example in section 2.1.2.1 (Figure 2.4(c)).The minimum utility design to sample problem shown in Figure 2.11 has one more unit than the definite minimum according to Equation 7. Hence there must be a loop in the design.Figure 2.24(a) shows this loop by dashed lines.

An important feature of every loop is that heat loads can be shifted around the loop from one unit to another.The load is subtracted from one unit, added to the next in the loop, subtracted from the next and so on around the loop.Again for the sample problem, the exchangers forming the loop are 2 and 4.Note that unit 3 is not a part of it.

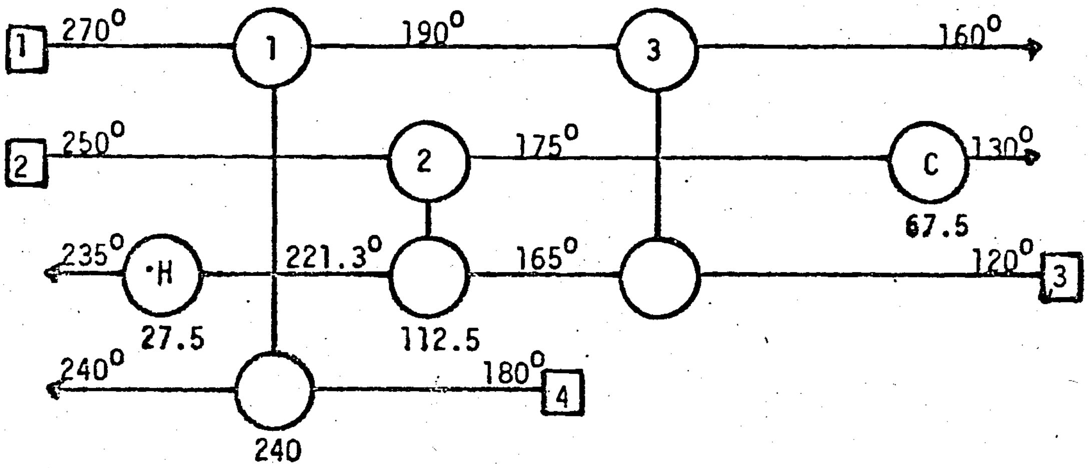
The load shifts always maintains the correct stream heat loads but the exchanger duties are changed and may



(a) Identifying a heat load loop



(b) Structure after loop-breaking



(c) The relaxed solution

Figure 2.24- Sample problem energy relaxation

cause a violation of ΔT_{min}.However, driving forces can be restored using heat load paths.

A path is a continious connection in the grid between a heater, heat exchangers and a cooler.Figure 2.24(b) shows the simplest form of a path.

Load shifts along paths follow equivalent rules to load shifts around a loop.Load is added to a heater, subtracted from an exchanger, added to the next exchanger in the path, subtracted from the next, and so on along the path until it is finally added to a cooler.Stream enthalpy balance is maintained but exchanger loads and operating temperatures are changed.This last feature means that a path can be used to restore driving forces.

It is now apparent that load shifts around loops can form the basic mechanism for the reduction in the number of units.When the load shift around a loop leads to a reduction in the heat load of a unit which equals the load on that unit then the unit is removed from the design and the number of units is reduced by one.Back to sample problem, we may now discuss this procedure.

A good choice of exchanger to remove is exchanger No. 4 as it has the smaller load when compared with exchanger No. 2.Figure 2.24(b) shows the topology and temperatures after the load of match No. 4 has been transferred to exchanger No. 2.The heat load of exchanger No. 2 has now become 120 kW while the loads of all other units are unchanged as they were not part of the original loop.There is now a violation in ΔT_{min} as reflected by the difference in temperatures 170 °C and 165 °C.However, ΔT_{min} can be restored using the heat load path shown in the same figure.If we add a heat load X to the heater, then by enthalpy balance the load on match 2 must be reduced by X and the load on the cooler increased by X.Effectively we have introduced extra heat X to the network, thereby reducing the load on match 2 by X.Here, we should keep in mind what has been indicated earlier: Match No. 3 is not a part of the original loop so we can not change temperature of stream 3 on the hot side of match 3 (165 °C).What we have to do is to calculate X that will increase the temperature of stream 2 on the cold side of match 2 to 175 °C or in other words to formulate T = f(X).

$$T = 250^{\circ} - \frac{(120 - X)}{1.5} = 175^{\circ}$$

Alternatively, applying the same logic to the cooler,

$$T = 130^{\circ} + \frac{(60 + X)}{1.5} = 175^{\circ}.$$

Solving either of the above equations yields X = 7.5 kW. Since ΔT_{min} is exactly restored 7.5 kW must be the minimum energy sacrifice to produce a design with minimum number of units.The relaxed solution is shown in Figure 2.24(c).

It is important to distinguish between the elimination of units using heat load loops and paths and the mere replacement of units by heaters and coolers.Consider again the design shown in Figure 2.24(a). The number of units can obviously be reduced by substituting exchanger No. 4 with an increased heater load on stream No. 3 and an increased cooler load on stream No. 2.The removal of exchanger No. 4, in this case, would necessitate a 30 kW increase in both hot and cold utility usage.By first redistributing the exchanger load using a loop as above we found that the hot and cold utility increase was only 7.5 kW.This is a substantial improvement over the 30 kW penalty incurred if the exchanger is simply substituted.

Moreover, it is worth emphasising that the ΔT_{min} constraint should not always be restored after a load shift around a loop. Consider again Figure 2.24(b) which shows a topology from sample problem after loop-breaking.Although a ΔT_{min} violation occurs the network is still thermodynamically feasible.

Figure 2.25 illustrates some other aspects of loops and paths.The loop in Figure 2.24(a) is a simple one involving only two units. In Figure 2.25(a) a more complex one is shown involving four units.However, the loop can be broken in exactly the same way, that is

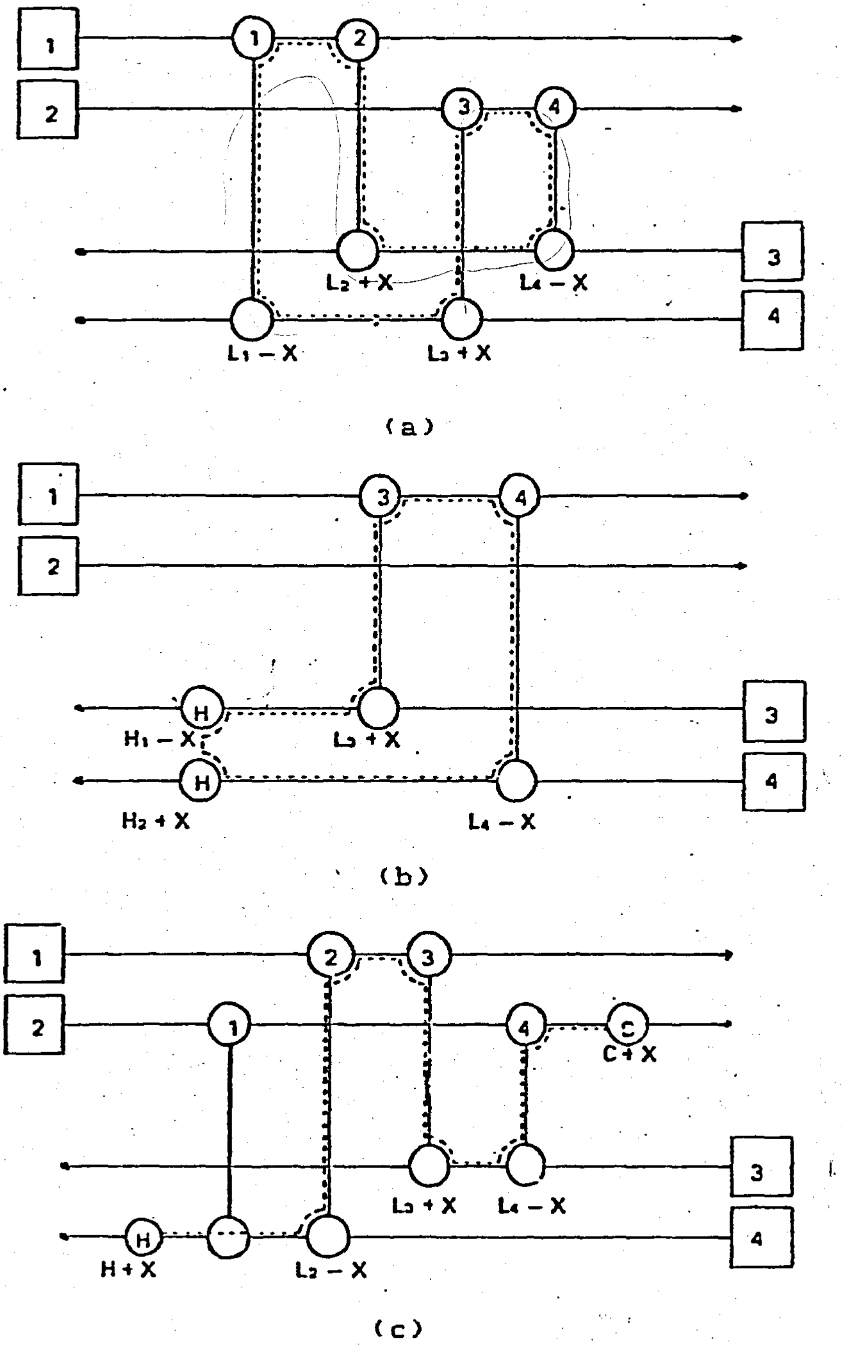


Figure 2.25- Complex loops and paths [4]

adding and subtracting X units on alternative matches round the loop. In Figure 2.25(a) the loop breaks when X equals either L_1 or L_4. Note that the adding and subtracting could have been done in the alternative way, in which case it would break when X equals either L_2 or

L_3.In other words, there are two ways of breaking the loop.This is true of the loop in Figure 2.24(a)(90 kW could have been subtracted from match 2 and added to match 4), and in fact is true of all loops.It is not possible a priori to say which way will lead to the smallest energy relaxation.A good rule of thumb given by Linnhoff et. al.[4] is to go for the way that removes the smallest unit.Note that, when there are, say, two loops in a system, it may be possible to trace out more than two closed routes.This should not cause confusion if it is realised that the number of independent loops is always equal to the number of excess units (> N-1) in the system.Note too that loops can include heaters and coolers, as illustrated in Figure 2.25(b).

A complex path is shown in Figure 2.25(c), and again the alternate addition and subtraction of the load X works in just the same way as for the simple path.Note that although the path goes through match No. 1 in this example, match No. 1 is not a part of it.Its load is not changed by the energy relaxation, but the temperatures on stream No. 4 on either side of it are changed.When a similar situation occurs within a loop it is possible for the exchanger that does not undergo a load change to become infeasible.Hence the need to recalculate all temperatures after loop-breaking.

2.2.5 Design for the Multiple Utilities Case

So far in the discussion, the possibility of using many utility levels has not been considered.This is clearly unrealistic, and a method is required to deal with the problem.In the Problem Table algorithm for energy targeting, the implicit assumption is that hot utility is hot enough to perform any required heating duty, and that cold utility is cold enough for any cooling duty.The Problem Table can however be adapted to cater for the multiple utilities case [4].

2.2.5.1 The Grand Composite Curve

Figure 2.26(a) shows a schematic heat cascade diagram (of the type introduced in section 2.2.1.2). The pinch divides the cascade into the process heat sink above pinch temperature, and the process heat source below pinch temperature. The heat sink above the pinch and the heat source below can be characterised as shown in Figure 2.26(b). The heat flows from the cascade on the left of Figure 2.26(b) are shown plotted against their respective interval boundary temperatures in the graph on the right.The result is a graph which characterises the process source and sink in temperature-enthalphy terms [28]. The graph above the pinch represents a sort of "net process cold stream" against which hot utilities can be matched in countercurrent flow.See the top parts of Figures 2.27(a) and (b).Similarly the graph below the pinch represents a sort of "net process hot stream"

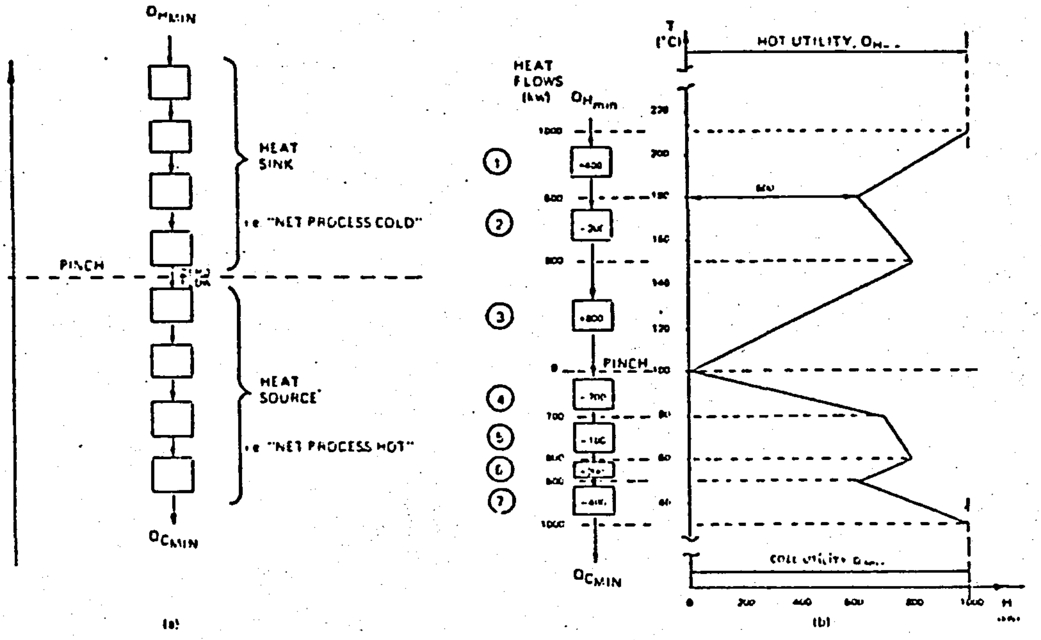


Figure 2.26- Construction of the Grand Composite Curve [4]

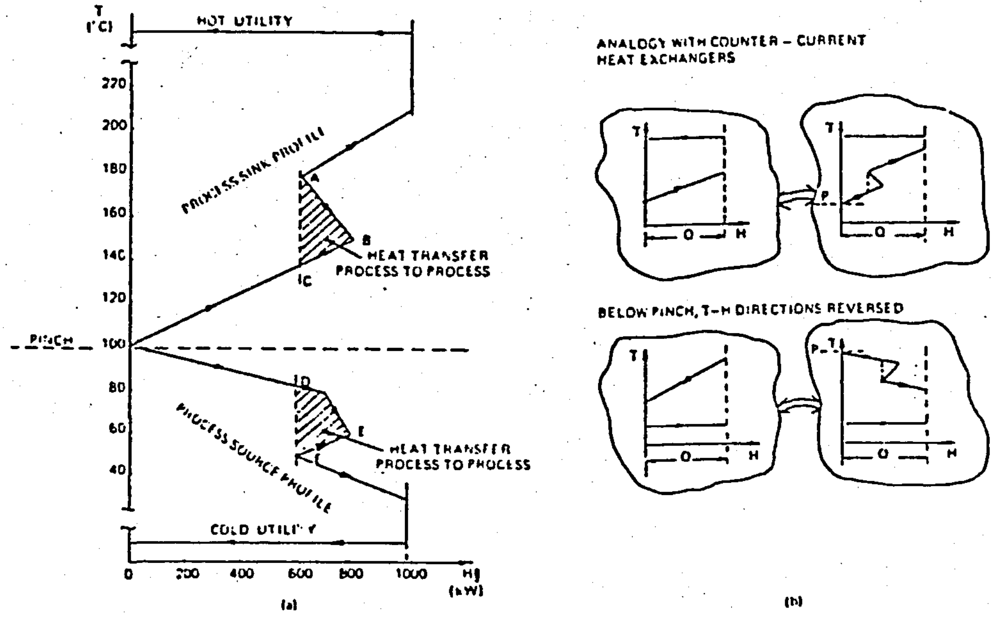


Figure 2.27- Interpretation of the Grand Composite Curve

against which cold utilities can be matched countercurrently.See the bottom parts of Figures 2.27(a) and (b).Note though that below the pinch the net process hot stream (from now on it will be called "process source profile") runs in the reverse direction to that previously used for hot streams. This arises simply out of the construction method shown in Figure 2.26(b). There is little point, however, in dissecting the graph to turn the process source profile around to make it consistent with the more usual hot stream representation.In fact there is a positive advantage in leaving it as it is. The point of gradient change at zero heat flow where the process source profile and the process sink profile (i.e. the net process cold stream) meet, clearly represents the pinch.

In the shaded regions shown in Figure 2.27(a) the analogy with single stream heat exchange breaks down. Above the pinch, section AB of the graph represents the heat surplus temperature interval No.2(Figure 2.26(b)). It therefore represents a "local" heat source in the midst of the net process heat sink. Similarly below the pinch, section FE represents a local heat sink (interval No.6) in the midst of the net process heat source.By the heat cascading principle, the heat available in AB is hot enough to be transferred into the process sink anywhere between the pinch and point B.However,if it is transferred into CB, then it is transferred at the minimum possible driving force. This allows the best possible use of low temperature hot utilities (i.e. over the region between the pinch and point C). Similarly, if below the pinch the heat required by FE is taken from DE, the best possible use can be made of high temperature cold utilities. Thus in the shaded regions in Figure 2.27(a), the process effectively takes care of itself, i.e., it is in enthalpy balance.It is only those parts of the graph outside these regions that represent the process source and sink profiles.

Normally, the designer wants to maximise the use of the least expensive utilities. This in turn usually means that we want to maximise the use of the coldest hot utility and the hottest cold utility. The above the pinch graph from Figure 2.26(b) is reproduced in Figure 2.28(a). Suppose the lowest level steam available on the site has a condensing temperature of 165 °C, and that ΔT_{min} for the network problem is 10 °C.When plotting this level on the grand composite curve, it must be plotted at (165 °C -1/2 ΔT_{min}) 160 °C.This is because all temperatures in the grand composite curve are interval boundary temperatures, i.e. 5 ° below hot stream temperatures and 5 °C above cold stream temperatures.The utility line numbered 1 in Figure 2.28(a) at 160 °C represents the steam at 165 °C. It shows that the maximum amount of steam that can be supplied at this level 600 kW. The other 400 kW must be supplied from high pressure steam. Another question that may rise at this step is related with the minimum temperature of the low pressure steam. The answer is given by the utility line numbered 2, showing that 600 kW can just be supplied at an interval boundary temperature of 137.5 °C, i.e. a steam condensing temperature of 142.5 °C. If the low pressure

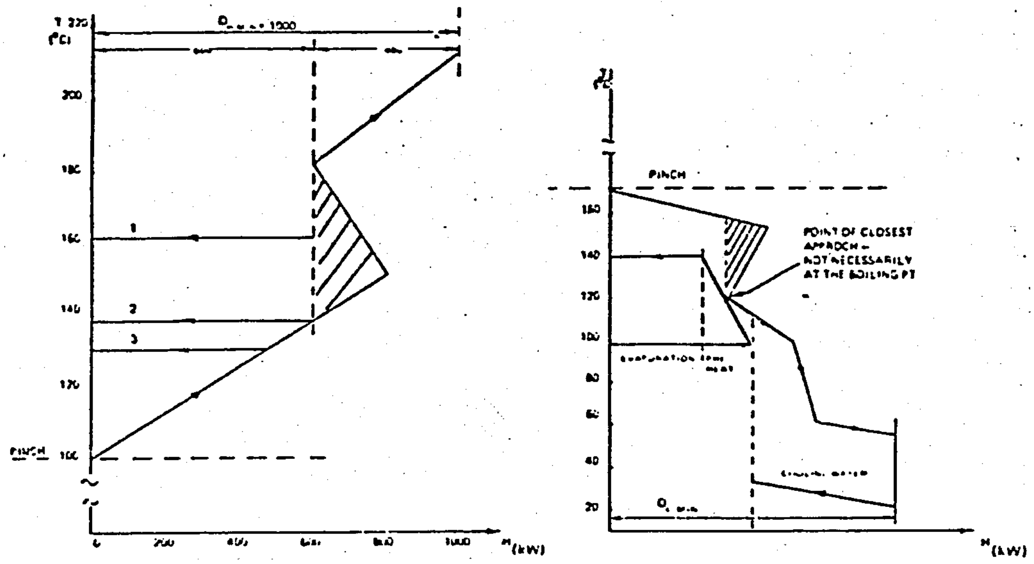


Figure 2.28- Use of the Grand Composite Curve for multiple utilities targeting [4]

steam level is lowered any further, then the amount that can be supplied from it must fall. So, for example, if the steam condensing temperature is 135 °C (utility line 3), then only 480 kW can be supplied at this level and high pressure steam must be increased from 400 to 580 kW.

Figure 2.28(b) shows similar principles applied to cold utilities placed below the pinch (now, on a different example). It is desired to raise steam for the low pressure main at 140 °C interval boundary temperature. If the designer wants to find what is the maximum amount of steam-raising possible against the given process source profile. Knowing the shape of the steam-raising pre-heat/evaporation from physical properties, it can be constructed on the graph so that it just touches the process source profile at some point. The profile that it just touches gives the maximum steam-raising possible, as shown in Figure 2.28(b). The rest of the utility cooling must be done by lower temperature utility, in this case cooling water. Note that the point of closest approach for the steam-raising line is not necessarily at the saturation point. Note too that the variable temperature cooling water is truly represented.

2.2.5.2 Designing for Many Utilities

The Grand Composite Curve constructed from Problem Table analysis can be used as a design tool by the engineer wanting to specify utilities. Using the objective of maximising the use of the least expensive utilities, the shape of the grand composite curve often dictates the most appropriate choice of levels and loads. This is illustrated in Figure 2.29(a). However, in many processes there is no "natural" choice of utility levels and loads, as illustrated in FIgure 2.29(b). Several choices and combinations of choices are possible in the low temperature region of this problem. Using many levels in this region clearly reduces driving forces between utilities and process, and so reduces the operating cost for steam-raising etc. However, each extra level "costs" complexity in design. The designer needs to balance the gain in running cost against the increased capital cost brought about by increasing the number of levels.

Design with multiple utilities will now be illustrated by an example. The process stream data are

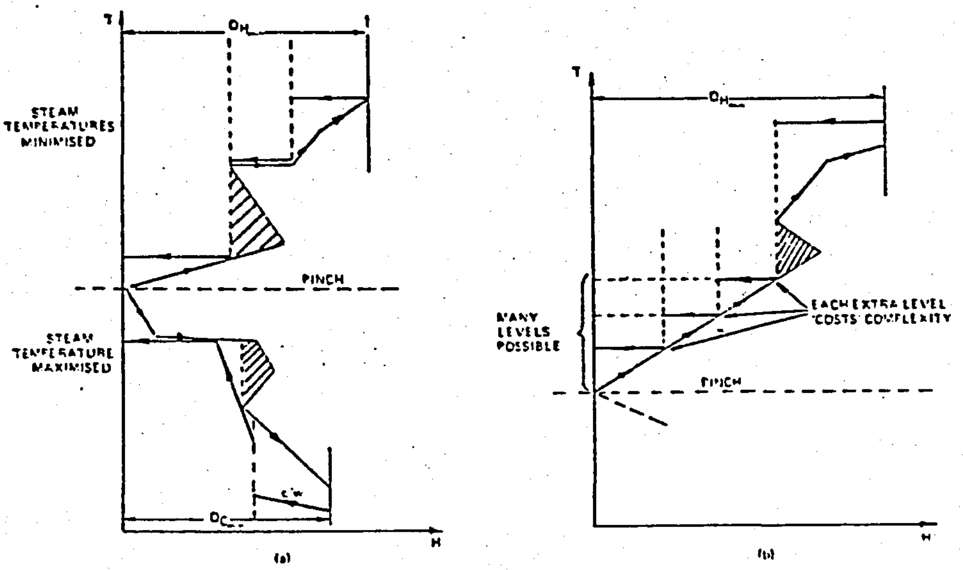


Figure 2.29- Use of the Grand Composite Curve for fixing utility levels [4]

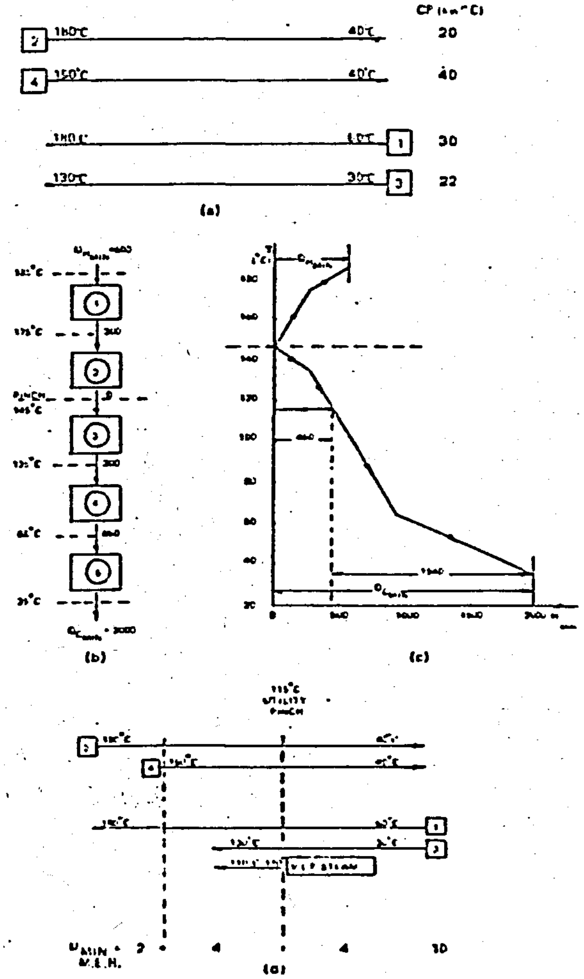


Figure 2.30- Multiple utilities example: targeting [4]

given in Figure 2.30(a). If this data set is analysed by the Problem Table method for ΔT_{min}=10 °C, then the cascade diagram shown in Figure 2.30(b) is obtained. From this diagram, the Grand Composite Curve shown in Figure 2.30(c) can be plotted. Suppose that, VLP (very low pressure) steam at 110 °C from feed water at the same temperature is asked to be raised.If the global ΔT_{min} of 10 °C also applies to utilities, then the cold utility line for the VLP must be drawn under the process source profile at 115 °C. This is shown in Figure 2.30(c), where it is also shown that the maximum VLP steam-raising possible is 460 kW out of a total cold utility requirement of 2000 kW.

Having obtained the energy targets for the problem, obtaining the number of units target is shown in Figure 2.30(d). Note that in the grid representation the VLP cold utility has been drawn as a cold stream. In general, wherever utilities fall within the temperature range of process streams they should be drawn in the same way as process streams. This is because temperature cannot be ignored in relation to these intermediate utilities.

The network can now be designed by the "Pinch Design Method", yielding the solution shown in Figure 2.31(a). The philosophy of the Pinch Design Method is to start the design at the pinch and move away.However, where there are two pinches, designing away from each into the region in between them can clearly lead to a confusion.The

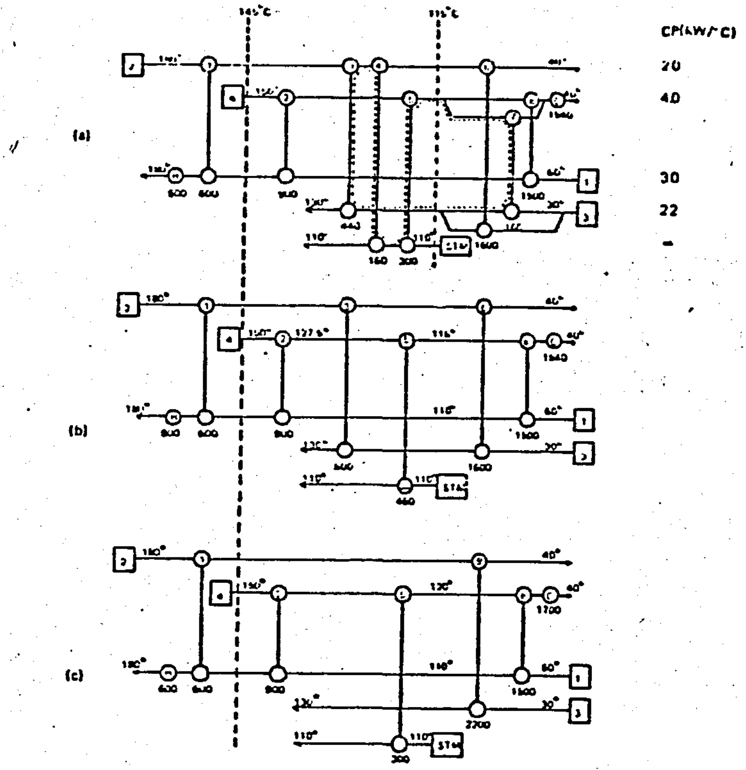


Figure 2.31- Multiple utilities example: design [4]

recommendation by Linnhoff et.al.[4] governing this situation is to design away from the most constrained pinch first.Hence in Figure 2.31(a), above the 115 °C pinch ($CP_H \le CP_C$) stream 4 must be matched with steam-raising (whose CP is infinity) but stream 2 can be matched with any of the cold streams.Below the 145 °C pinch, however, ($CP_H \ge CP_C$), stream 1 must be matched against stream 4. There are no options. Hence this is the first design step, ticking off stream 1 between the pinches (match 2). As already mentioned, match 5 is essential, and ticks off the residual on stream 4.Stream 2 can then be brought down to the 115 °C pinch by matching either against stream 3 or against steam-raising. In Figure 2.31(a) it is matched against steam-raising (match 4), leaving match 3 to tick off stream 3 and the residual on stream 2.If stream 2 has been brought down to the 115 °C pinch by stream 3 instead of steam-raising, matches 3 and 4 would simply have ended up in the opposite sequence.

Design above the 145 °C pinch is straightforward by the pinch design method.Design below the 115 °C pinch, however, requires streams 3 and 4 each to be split into parallel branches.

A maximum energy recovery design has been produced having two pinches and consequently having 10 units as demonstrated in Figure 2.30(d). At this step the designer wants to see what simplification can be achieved by sacrificing some of the VLP steam-raising, switching it to cooling water.If the 115 °C utility pinch is removed, the units target for the whole problem becomes seven.The scope for simplification is therefore three units.Also, the two stream splits should not be needed. Breaking the loop shown in dotted line in Figure 2.31(a) leads to the topology shown in Figure 2.31(b). Note that both matches 4 and 7 and the two stream splits disappear by this operation.Also, matches 3 and 6 can then simply be merged to form a new match (match 9 in Figure 2.31(c)). Hence three units are eliminated.Recalculating temperatures, matches 5 and 8 have a 4 °C ΔT_{min} violation. This can be restored by shifting 160 kW of load from VLP steam-raising to cooling water, giving the design shown in

Figure 2.31(c).

Thus by "backing off" to 65 percent of the maximum possible VLP steam-raising, a design is produced that saves three units and two stream splits.

2.2.6 Retrofit Design

So far the applications of Pinch Technique to "grassroots" design are handled. In this section another important subject, contributions to retrofit design will be summarised. There are few articles written on this subject [4,8,9,27,29] since main interest has been focused on grassroots design for several years.In fact, numerous installed plants have to be improved to save enery and capital.

As it is indicated by Tjoe and Linnhoff [27], a design engineer can not follow the rules of a grassroots design to reach a good retrofit. A good retrofit exploits opportunities and may make the process quite different from the optimum grassroots design. It should always be kept in mind that, engineer has many installed units (a definite heat transfer area) in case of retrofit design and should use this area as effectively as possible. Following section gives an idea why grassroots and retrofit designs differ from each other.

2.2.6.1 Targeting Philosophy

Figure 2.32 shows an energy/area plot, which relates the energy requirement with the heat exchange area used in a given process. Point A represents a case where the composite curves are close (low ΔT_{min}),with corresponding high energy recovery but high investment in area. Point C represents a case with high ΔT_{min},yielding lower energy recovery but less investment. We have a continious curve representing networks that are all on target for both energy and area. Point B represents the optimum tradeoff with the lowest total cost and finally suppose that point X is the retrofit candidate.

The area below the curve is marked "infeasible" since it is not possible for a design to be better than target. Now the question is which direction to follow to improve the heat recovery properties of the existing design. The ideal point to aim for from X is not B since we can not discard existing area as explained above.We should try to improve on the ineffective use of area due to criss-crossing (see Figure 2.14), while shifting the composite curves closer to save energy. So, the ideal point should be A. Here we would save as much energy as possible using the existing area. However, in practical context,one has to invest some capital to make changes to an existing network, thus increasing area.

In Figure 2.33, many paths with different cost effectivenesses are shown. The lower the curve, the lower the investment for a given savings. The best curve is a function of plant layout and process constraints. Though

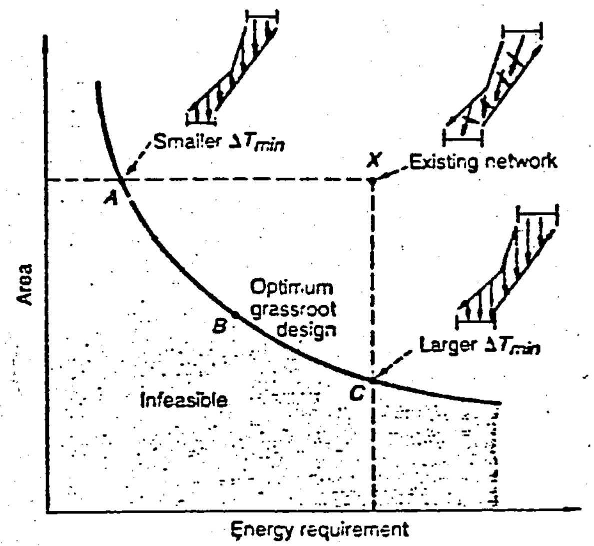


Figure 2.32- Alternative points on energy/area plot [27]

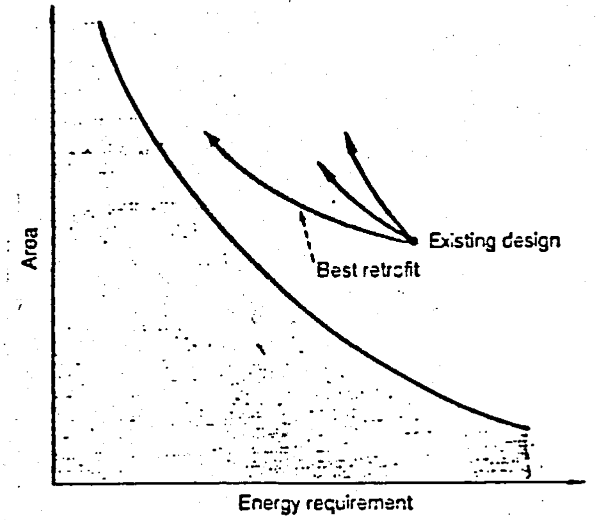


Figure 2.33- Paths with different cost effectivnesses [27]

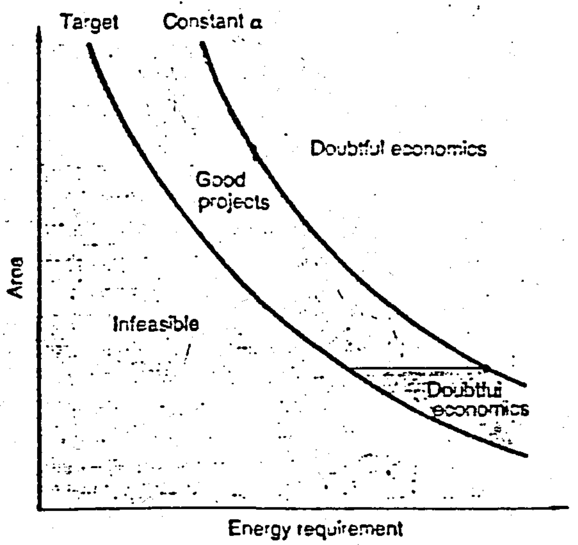


Figure 2.34- Four distinct regions in case of constant α [27]

it is indicated by Tjoe and Linnhoff [27] that some studies are carried out on understanding the functional form of the best curve , no results have been published yet.

2.2.6.2 Targeting Procedure

Prior to explaining the targeting procedure, an assumption should be made. The network , after retrofit, use area at least as effectively as before; if the project is good, then it is not likely to place new area that reduces the effectiveness of the area usage overall.

Area efficiency (α), a concept that is defined by Tjoe and Linnhoff [27], equals to the ratio of minimum area required (target) to the one actually used for a specific energy recovery:

$$\alpha = \left[\frac{A_{target}}{A_{existing}} \right]_{existing\ energy} \qquad (22)$$

The value of α can be expected to be less than unity in practical designs since $A_{existing} \geq A_{target}$.The equality applies when "no criss-crossing" takes place.The lower the value of α, the poorer the use of area, and the more severe the criss-crossing.As it is the case in the functional form of the best curve, no numerical values for α are proposed by Tjoe and Linnhoff.

Now, assuming that α is constant over the full energy span, one can define four distinct regions in the energy/area plot, Figure 2.34. A region in which designs are infeasible (be they retrofit or new design); two regions in which economic retrofits are not expected; and a fourth region within which good retrofits should fall.This curve forms a boundary for design and the engineer can now expect to find a challenging solution.

2.2.6.3 A Procedure for Retrofit Design

Below given a step by step method for retrofit design. This method, as indicated by Tjoe and Linnhoff, has been developed to feature a high degree of user interaction. Engineering judgement is required and influences the progress of the design.

A. Identify cross-pinch exchangers:

The network is drawn on the grid (using ΔT_{min} determined in the targeting stage) and the heat exchangers which transfer heat across the pinch are identified.

B. Eliminate cross-pinch exchangers:

The units recognised in Step A are removed from the grid.

C. Complete the network:

New exchangers are positioned and, where possible, units removed in Step B are reused. Since heat loads of the units change at the end of this step, new inlet and outlet temperatures should be computed.

D. Evolve improvements:

The engineer improves compatibility with existing network via heat load loops and paths. Use of loops introduces some flexibility into the design. This flexibility can be used to make old exchangers fit new duties.The paths also contribute to this flexibility.

Example problems solved by this procedure show significant improvements in heat recovery properties of the existing plants.

CHAPTER III

PROGRAMMING CONSIDERATIONS

This chapter includes the description of the programs developed during this study. A general information is followed by the presentation of main programs and subroutines.

3.1 General Information on Programs

The Pinch Technique which is explained in the preceeding chapter is formulated into two computer programs: HEXNET and DESIGN. The former determines the targets while the latter performs the synthesis of heat exchanger networks.

For convinience, the result files are given the same names with the programs, having additional extensions, ".RES". Both programs are easy to use and do not necessiate detailed information to run. An important point to keep in mind is the consistency of units of the data supplied to HEXNET.

Both programs are written in FORTRAN by using an Olivetti M24 PC. The memory needs are 128 kB for HEXNET and 131 kB for DESIGN.

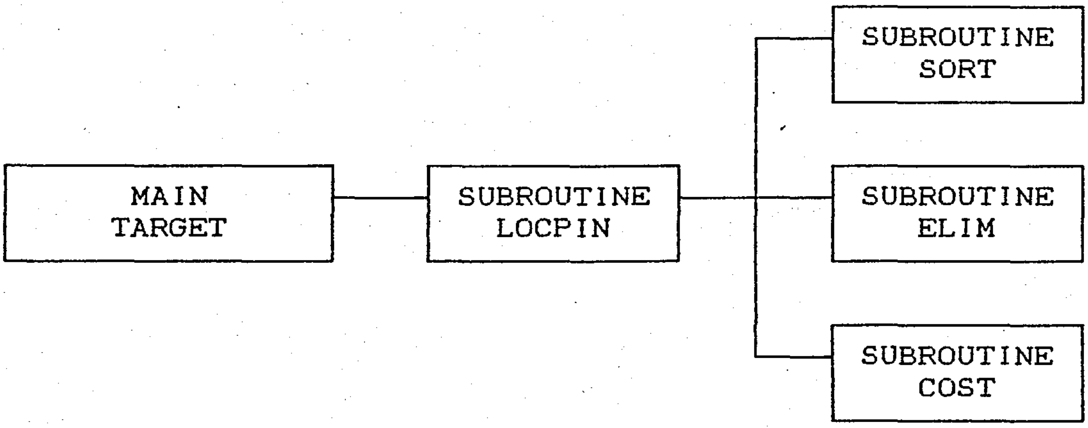


Figure 3.1- Structure of HEXNET

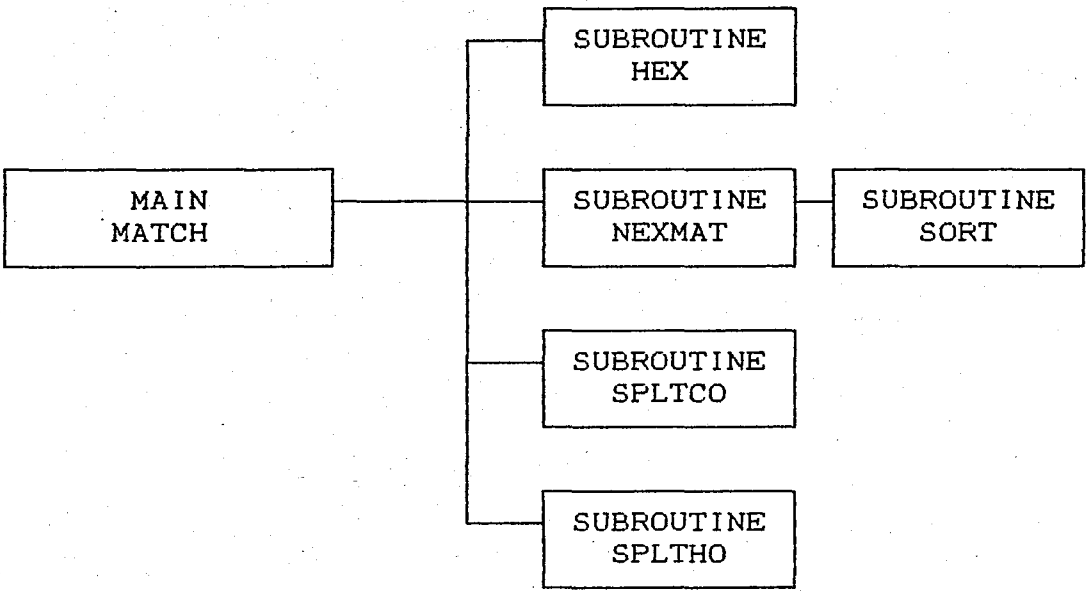


Figure 3.2- Structure of DESIGN

3.2 Structure of HEXNET

MAIN TARGET

Target is the main program of HEXNET. It reads the total number of process streams and calls LOCPIN for the determination of targets.

SUBROUTINE LOCPIN

This subroutine performs the calculations related with the determination of targets and pinch temperature.

Two data files and two result files are processed to maintain the connection between HEXNET and DESIGN and to tabulate the results.

One of the input files which is coded "STREAM.DAT" keeps the information about process streams. One can use the data already existing in this file or prefer interactive usage to give the properties of streams of a new problem. Thinking the possibility of entering a wrong data point - or running the same problem with little changes in stream properties -, the file operations are so arranged to accept such corrections.

The second input file is called "TECCAL.DAT". Technical data (e.g. values of cost parameters, temperature and latent of steam, inlet and maximum allowable outlet temperatures of cooling water, values of annual rate of return and equipment downtime etc.) are kept in this file. Two options, explained in case of

STREAM.DAT are also valid for the operation of TECCAL.DAT but this time, the user has no chance to correct any wrong input without re-running the whole program.

Having completed the data input, the next step is to read the prescribed ΔT_{min} value. If the user does not want to carry out calculations with a predetermined approach temperature, an outer optimization loop which employs Fibonacci Search is initiated. The lower and upper bounds on ΔT_{min} are arbitrarily chosen as 1 °C and 30 °C, respectively since experienced values often lie within this interval.

Using minimum approach temperature, subroutine LOCPIN computes the following by using the Problem Table algorithm mentioned in section 2.2.1.1.

(i) Interval boundary temperatures,

(ii) Heat capacity flow rates of subnetworks,

(iii) Heat deficit or surplus for each interval,

(iv) Minimum utility requirements and the pinch temperature.

Having determined minimum utility consumption target, the next step is the construction of T/H diagram of the problem to calculate minimum heat transfer area requirement. This task is performed by defining corner points of hot and cold superstreams. For the validity of Problem Table algorithm, the simple linearisation CP=constant should be acceptable. This enables us to characterise each temperature interval by a linear function;

$$T = f(H)$$

in the form of,

$$T = mH + n. \qquad (23)$$

In this equation, m is the slope of the line segment and n is the related corner point. Calculation of "m" values can be easily done since the designer has the necessary T and H data at corner points.

This correlation is very practical when dealing with the temperatures on a T/H diagram. Suppose, a corner point lies on the hot composite. To form an interval, projection of this point on the cold composite is necessary. Since a vertical line will be drawn downwards, the projected point will have the same enthalpy with the one on the hot composite. Knowing the values of m, n, and H, one can easily calculate the temperature of the cold composite at this point by using Equation 23. The same procedure applies for the temperatures to be determined on the hot composite. Determination of inlet and outlet temperatures of the superstreams within a particular section is necessary for the calculation of T_{LM} term of Equation 17 (see Chapter II). The overshoots of hot and cold composites are then used to compute the area of auxilary coolers and heaters.

Last target which is determined by HEXNET is the minimum number of heat exchanger units. Equation 7 is used for this task.

SUBROUTINE SORT

Subroutine SORT is used to put the elements of a vector in a decreasing order of magnitute.It is called several times by the main and subprograms to rank inlet, outlet temperatures and heat capacity flow rates of the process streams.

SUBROUTINE ELIM

ELIM is the code of the subroutine that is called by HEXNET to eliminate the duplications which may occur during the preparation of Problem Table.As it is explained in sub-section 2.2.1.1, adjusted temperatures of the hot streams and the supply and target temperatures of the cold streams should be ranked in decreasing order to get the interval boundary temperatures.Since the main aim is to partition the problem, repetetions have no meaning and need not be considered.

SUBROUTINE COST

Subroutine COST computes, (i) yearly based operating cost, (ii) annuilized capital cost and, (iii) the sum of these two items; the total cost of the system.

3.3 Structure of DESIGN

MAIN MATCH

MATCH is the main program of DESIGN. It consists of two parts. One of them is responsible for synthesis above the pinch temperature and the other below the pinch temperature. The below-the-pinch design criteria are the "mirror image" of those for above the pinch.

If the next match will be a pinch exchanger, streams that are chosen by NEXMAT as the candidates of the next match are tested by this main program to check whether they fulfill three design criteria (see section 2.2.3.2). If those criteria are not satisfied, stream splitting is considered as a solution. This task is performed according to the algoritms given in Figure 2.20.

The next step is the determination of the stream with smaller heat load or in other words the one that will be ticked-off. Knowing the heat load of the exchanger, one can calculate the inlet and outlet temperatures of the hot stream and its partner cold stream. Here, another constraint should be satisfied. This thermodynamic constraint necessiates ΔT_{min} being greater than or equal to a prescribed value.

If this criterion is violated, another cold stream (or another hot stream, if the design is carried out below the pinch) is searched by calling NEXMAT. If none of the cold (hot) streams satisfy the criteria mentioned above, stream splitting is applied. As it is indicated by Linnhoff et.al. [4] whenever the designer runs into trouble in applying the tick-off rule, he should attempt to find a stream split solution.

The final step in design is to place auxilary units. The remaining cold streams above the pinch are carried to their target temperatures by steam heaters and the remaining hot streams below the pinch are carried to their target temperatures by water coolers. This procedure also guarantees the development of a network which consumes utilities at a minimum level.

SUBROUTINE NEXMAT

Subroutine NEXMAT (NEXt MATch) determines the numbers of the hot and cold streams that will be matched presently.An integer parameter, BP, takes a value of zero or one indicating whether the design is carried out above or below the pinch.

For the hot end design, the hot stream with minimum outlet temperature and the cold stream with minimum inlet temperature are selected as the candidates of the streams of next match.If there exists more than one hot or cold stream with the qualifications given above, the one(s) having greatest heat capacity flow rate takes(take) the privilage of being matched beforehand.Subroutine SORT is called to put the temperatures (and if necessary, heat capacity flow rates) into a decreasing order.

For the cold end design, the hot stream with maximum inlet temperature and the cold stream with maximum outlet temperature are chosen.

This heuristic approach enables the designer to complete the pinch matches prior to ordinary ones.Remember that, one should start the design where the problem is most constrained (see Chapter II).Temperature constraints and the feasibility criteria are ignored by this subroutine.

SUBROUTINE SORT

This subroutine is utilised by both of the programs. See section 3.2 for its description.

SUBROUTINE HEX

Subroutine HEX (Heat EXchanger) reads the input and output temperatures and individual heat transfer coefficients of the hot and cold process streams and the heat load of the exchanger.It computes the logarithmic mean temperature difference, overall heat transfer coefficient, the area and the capital cost of this particular unit. Two labeled COMMON statements , DES1 and DES2, transfer data to this subroutine while the output is so arranged to tabulate some properties of the exchanger being designed.

SUBROUTINE SPLTHO

This subroutine performs the splitting of hot streams. According to the value of BP (an integer parameter), different strategies are employed for this task. If BP equals zero, a hot stream above the pinch point and if it equals unity, a hot stream below the pinch point is split.

An important item that is worth explaining is the procedure for the determination of split branch flows. As an initial approach, heat capacity flow rates of the branches are set equal to the CPs of their partner cold streams. This procedure enables us to maintain the CP equality criterion which is valid for pinch matches (see section 2.2.3.2.2). Then, by following the recommendation of Linnhoff et.al. [4], the final branch CPs are chosen according to the ratio between the heat loads of the branches and the load of the main hot stream being split.

SUBROUTINE SPLTCO

This subroutine performs the splitting of cold streams. The principles explained for SPLTHO are also valid for this subroutine.

CHAPTER IV

EXAMPLE PROBLEMS SOLVED BY HEXNET AND DESIGN AND A COMPARISON OF METHODS

This chapter is devoted to the comparisons of the solutions of some standard problems from the literature.Since design data do not vary too much from one problem to another, a general table is sufficient to list all technical and economic properties.

For each problem, an original output of HEXNET

TABLE 6. DESIGN DATA FOR SAMPLE PROBLEMS

STEAM:
Pressure (lb/in.^{2}abs): 962.5 (for 4SP1)
: 450.0 (for all other problems)
Latent Heat (Btu/lb.): 656.6 (for 4SP1)
: 768.0 (for all other problems)
Temperature (°F) : 540.0 (for 4SP1)
: 456.0 (for all other problems)
COOLING WATER:
Temperature : 100.0 °F
Heat capacity : 1.0 Btu/lb °F
Maximum output Temp. : 180.0 °F
MINIMUM ALLOWABLE APPROACH TEMPERATURES:
Heat exchanger : 20 °F
Steam heater : 25 °F
Water cooler : 20 °F
OVERALL HEAT TRANSFER COEFFICIENTS:
Heat exchanger : 150 Btu/hr ft^2 °F
Steam heater : 200 Btu/hr ft^2 °F
Water cooler : 150 Btu/hr ft^2 °F
EQUIPMENT DOWN TIME:
380 hr/yr for 4SP1, 5SP1 and 6SP1
260 hr/yr for 4SP2, 7SP1, 7SP2 and 10SP1
NETWORK COST PARAMETERS:
$a = 350$, $b = 0.6$, $\delta = 0.1$
UTILITY COSTS:
Cooling water cost : 0.00005 $/lb
Steam cost : 0.00100 $/lb

tabulating the stream data and an output of DESIGN tabulating the network structure are included. A brief discussion follows the comparison table and gives some information about the networks developed by various methods.

```
 -----------------------------------------------------------------------------
I                                                                             I
I                          STREAM DATA FOR 4SP1                               I
I_____________________________________________________________________________I
I                                                                             I
I MINIMUM APPROACH TEMPERATURE:   20.00                                       I
I_____________________________________________________________________________I
I NUMBERI  TYPE I TEMPERATURE I (*) HEAT I     HEAT     I       I              I
I   OF  I   OF  I_____________I CAPACITY I   TRANSFER   I PHASE I              I
I STREAMI STREAMI  IN  I  OUT I FLOW RATEI COEFFICIENTI CHANGEI    HEAT LOAD  I
I_______I_______I______I______I__________I____________I_______I______________I
I       I       I      I      I          I            I       I              I
I   1   I   HOT I 320.0I 200.0I 16666.80 I  300.00000 I   NO  I  2000016.0000I
I_______I_______I______I______I__________I____________I_______I______________I
I       I       I      I      I          I            I       I              I
I   2   I   HOT I 480.0I 280.0I 20000.00 I  300.00000 I   NO  I  4000000.0000I
I_______I_______I______I______I__________I____________I_______I______________I
I       I       I      I      I          I            I       I              I
I   1   I  COLD I 140.0I 320.0I 14450.10 I  300.00000 I   NO  I -2601018.0000I
I_______I_______I______I______I__________I____________I_______I______________I
I       I       I      I      I          I            I       I              I
I   2   I  COLD I 240.0I 500.0I 11530.00 I  300.00000 I   NO  I -2997800.0000I
I_______I_______I______I______I__________I____________I_______I______________I
I                                                                             I
I               (*) in case of phase change  MASS FLOW RATE                   I
I_____________________________________________________________________________I

            MINIMUM APPROACH TEMPERATURE: 20.00
            NUMBER OF SUBNETWORKS:  7
            PINCH TEMPERATURE HOT END:480.00
                              COLD END:460.00
            MINIMUM UTILITY HEATING:   461200.0000
            MINIMUM UTILITY COOLING:   862398.2000
```

TABLE 7. STREAM DATA FOR 4SP1

```
 ---------------------------------------------------------------------------
I                                                                           I
I                         DESIGN TABLE FOR 4SP1                             I
I___________________________________________________________________________I
I     I NUMBER OF I    INLET     I    OUTLET    I        I  OVERALL   I          I
I     I  STREAM   I TEMPERATURESI TEMPERATURESI        I    HEAT    I          I
I HEX I___________I_____________I_____________I  HEAT  I TRANSFER   I   AREA   I
I  #  I HOT I COLDI  HOT I COLD I  HOT I COLD I  LOAD  ICOEFFICIENTI          I
I_____I_____I_____I______I______I______I______I________I___________I__________I
I     I     I     I      I      I      I      I        I           I          I
I   1 I  ST I   2 I540.00I460.00I540.00I500.00I .46E+06I   .20E+03 I  40.0    I
I_____I_____I_____I______I______I______I______I________I___________I__________I
I     I     I     I      I      I      I      I        I           I          I
I   1 I   2 I   2 I480.00I240.00I353.17I460.00I .25E+07I   .15E+03 I  315.    I
I_____I_____I_____I______I______I______I______I________I___________I__________I
I     I     I     I      I      I      I      I        I           I          I
I   2 I   2 I   1 I353.17I218.73I280.00I320.00I .15E+07I   .15E+03 I  213.    I
I_____I_____I_____I______I______I______I______I________I___________I__________I
I     I     I     I      I      I      I      I        I           I          I
I   3 I   1 I   1 I320.00I140.00I251.74I218.73I .11E+07I   .15E+03 I  71.3    I
I_____I_____I_____I______I______I______I______I________I___________I__________I
I     I     I     I      I      I      I      I        I           I          I
I   4 I   1 I  CW I251.74I100.00I200.00I180.00I .86E+06I   .15E+03 I  67.6    I
I_____I_____I_____I______I______I______I______I________I___________I__________I
```

TABLE 8. DESIGN TABLE FOR 4SP1

```
I-------------------------------------I------------------------I------------------------I
I                                     I                        I                        I
I                                     I         TARGET         I         DESIGN         I
I_____________________________________I________________________I________________________I
I                                     I                        I                        I
I  HEAT TRANSFER AREA                 I         665.3          I         706.4          I
I_____________________________________I________________________I________________________I
I  NUMBER OF HEAT EXCHANGERS          I                        I                        I
I         ABOVE THE PINCH POINT       I           1            I           1            I
I         BELOW THE PINCH POINT       I           4.           I           4            I
I         OVERALL                     I           5            I           5            I
I_____________________________________I________________________I________________________I
I                                     I                        I                        I
I  HOT UTILITY CONSUMPTION            I       .4612E+06        I       .4612E+06        I
I_____________________________________I________________________I________________________I
I                                     I                        I                        I
I  COLD UTILITY CONSUMPTION           I       .8624E+06        I       .8624E+06        I
I_____________________________________I________________________I________________________I
I                                     I                        I                        I
I  OPERATING COST                     I       .1040E+05        I       .1040E+05        I
I_____________________________________I________________________I________________________I
I                                     I                        I                        I
I  INVESTMENT COST                    I       3537.            I       3188.            I
I_____________________________________I________________________I________________________I
I                                     I                        I                        I
I  TOTAL COST                         I       .1394E+05        I       .1359E+05        I
I_____________________________________I________________________I________________________I

      NUMBER OF INDEPENDENT HEAT LOAD LOOPS IS:                   0
```

TABLE 9. PROPERTIES OF THE SOLUTION OF 4SP1

SAMPLE PROBLEM : 4SP1
INTRODUCED BY : Lee,Masso,Rudd [20]

AUTHOR(S)	REFERENCE #	TOTAL COST ($/yr)
Linnhoff,Flower	15	13587
Nishida,Liu,Lapidus	2	13590
Rathore,Powers	17	13573
Pho,Lapidus	13	13685
Kelahan,Gaddy	30	10634
Lee,Masso,Rudd	20	13481
Ponton,Donaldson	21	13534
Mc Galliard,Westerberg	2	13615
HEXNET		13590

TABLE 10. COMPARISON TABLE FOR 4SP1

The network developed by DESIGN was also found by Rathore and Powers , Nishida et.al., and Linnhoff and Flower. However, a different network was reported by Lee et.al., Mc Galliard and Westerberg , and Pho and Lapidus. The annual costs of the network reported by these investigators are $13481, $13615, and $13685, respectively. Using the data of Nishida et.al. their solution costs $13688/yr. This discrepancy in costs due to round-off values of stream properties and/or slightly different design data.

The configuration obtained by Kelahan and Gaddy is not feasible since ΔT_{min} constraint is violated in their solution. The value they have allowed in their solution is 0.6 °C which contradicts with the one accepted by most of the investigators, i.e., 20 °C.

```
 -----------------------------------------------------------------------------
I                                                                             I
I                          STREAM DATA FOR 4SP2                               I
I_____________________________________________________________________________I
I                                                                             I
I MINIMUM APPROACH TEMPERATURE:   20.00                                       I
I_____________________________________________________________________________I
I NUMBERI  TYPE I TEMPERATURE I (*) HEATI    HEAT    I       I               I
I   OF  I   OF  I_____________I CAPACITYI  TRANSFER  I PHASE I               I
I STREAMI STREAMI  IN  I  OUT I FLOW RATEI COEFFICIENTI CHANGEI   HEAT LOAD   I
I_______I_______I______I______I__________I____________I_______I_______________I
I       I       I      I      I          I            I       I               I
I   1   I  HOT  I 500.0I 110.0I 20000.00 I 300.00000  I  NO   I   7800000.0000I
I_______I_______I______I______I__________I____________I_______I_______________I
I       I       I      I      I          I            I       I               I
I   2   I  HOT  I 430.0I 230.0I 50000.00 I 300.00000  I  NO   I  10000000.0000I
I_______I_______I______I______I__________I____________I_______I_______________I
I       I       I      I      I          I            I       I               I
I   3   I  HOT  I 400.0I 110.0I 30000.00 I 300.00000  I  NO   I   8700000.0000I
I_______I_______I______I______I__________I____________I_______I_______________I
I       I       I      I      I          I            I       I               I
I   1   I COLD  I  25.0I 420.0I 70000.00 I 300.00000  I  NO   I -27650000.0000I
I_______I_______I______I______I__________I____________I_______I_______________I
I                                                                             I
I               (*) in case of phase change  MASS FLOW RATE                   I
I_____________________________________________________________________________I

           MINIMUM APPROACH TEMPERATURE: 20.00
           NUMBER OF SUBNETWORKS:  6
           PINCH TEMPERATURE HOT END: 45.00
                             COLD END: 25.00
           MINIMUM UTILITY HEATING: 1150000.0000
           MINIMUM UTILITY COOLING:         .0000
```

TABLE 11. STREAM DATA FOR 4SP2

DESIGN TABLE FOR 4SP2

HEX #	NUMBER OF STREAM		INLET TEMPERATURES		OUTLET TEMPERATURES		HEAT LOAD	OVERALL HEAT TRANSFER COEFFICIENT	AREA
	HOT	COLD	HOT	COLD	HOT	COLD			
1	2	2	430.00	25.00	230.00	410.00	.10E+08	.15E+03	839.
2	1	4	500.00	25.00	110.00	424.61	.78E+07	.15E+03	649.
3	3	3	400.00	25.00	110.00	350.00	.87E+07	.15E+03	.129E+04
4	ST	1	456.00	403.57	456.00	420.00	.12E+07	.20E+03	132.

TABLE 12. DESIGN TABLE FOR 4SP2

	TARGET	DESIGN
HEAT TRANSFER AREA	2433.	2911.
NUMBER OF HEAT EXCHANGERS		
ABOVE THE PINCH POINT	4	4
BELOW THE PINCH POINT	0	0
OVERALL	4	4
HOT UTILITY CONSUMPTION	.1150E+07	.1150E+07
COLD UTILITY CONSUMPTION	.0000	.0000
OPERATING COST	.1273E+05	.1273E+05
INVESTMENT COST	6444.	6919.
TOTAL COST	.1917E+05	.1965E+05

NUMBER OF INDEPENDENT HEAT LOAD LOOPS IS: 0

TABLE 13. PROPERTIES OF THE SOLUTION OF 4SP2

SAMPLE PROBLEM : 4SP2
INTRODUCED BY : Ponton,Donaldson [21]

AUTHOR(S)	REFERENCE #	TOTAL COST ($/yr)
Linnhoff,Flower	15	19567
Nishida,Liu,Lapidus	2	20353
Ponton,Donaldson	21	23742
HEXNET		19647

TABLE 14. COMPARISON TABLE FOR 4SP2

The solution presented by Ponton and Donaldson is a cyclic arrangement and features four different matches between the same two streams.

Nishida et.al., however, showed a further significant saving was possible if parallel splitting of cold stream No.1 was considered and presented a solution costing $20353/yr.

The solution of DESIGN was previously announced by Linnhoff and Flower. The difference that is observed between the costs is probably due to slightly different design data.

```
 ------------------------------------------------------------------------------
I                                                                              I
I                          STREAM DATA FOR 5SP1                                I
I______________________________________________________________________________I
I                                                                              I
I MINIMUM APPROACH TEMPERATURE:   20.00                                        I
I______________________________________________________________________________I
I NUMBERI  TYPE I TEMPERATURE I (*) HEAT I     HEAT     I       I              I
I   OF  I   OF  I_____________I CAPACITY I   TRANSFER   I PHASE I              I
I STREAMI STREAMI  IN  I  OUT I FLOW RATEI COEFFICIENTI CHANGEI   HEAT LOAD    I
I_______I_______I______I______I__________I_____________I______I_______________I
I       I       I      I      I          I             I      I               I
I   1   I   HOT I 480.0I 250.0I 31500.00 I  300.00000  I  NO  I  7245000.0000I
I_______I_______I______I______I__________I_____________I______I_______________I
I       I       I      I      I          I             I      I               I
I   2   I   HOT I 400.0I 150.0I 25200.00 I  300.00000  I  NO  I  6300000.0000I
I_______I_______I______I______I__________I_____________I______I_______________I
I       I       I      I      I          I             I      I               I
I   1   I  COLD I 100.0I 400.0I 21600.00 I  300.00000  I  NO  I -6480000.0000I
I_______I_______I______I______I__________I_____________I______I_______________I
I       I       I      I      I          I             I      I               I
I   2   I  COLD I 150.0I 360.0I 24500.00 I  300.00000  I  NO  I -5145000.0000I
I_______I_______I______I______I__________I_____________I______I_______________I
I       I       I      I      I          I             I      I               I
I   3   I  COLD I 200.0I 400.0I 24700.00 I  300.00000  I  NO  I -4940000.0000I
I_______I_______I______I______I__________I_____________I______I_______________I
I                                                                              I
I                 (*) in case of phase change  MASS FLOW RATE                  I
I______________________________________________________________________________I

            MINIMUM APPROACH TEMPERATURE: 20.00
            NUMBER OF SUBNETWORKS:  8
            PINCH TEMPERATURE HOT END:120.00
                             COLD END:100.00
            MINIMUM UTILITY HEATING: 3020000.0000
            MINIMUM UTILITY COOLING:        .0000
```

TABLE 15. STREAM DATA FOR 5SP1

DESIGN TABLE FOR 5SP1

HEX #	NUMBER OF STREAM HOT	NUMBER OF STREAM COLD	INLET TEMPERATURES HOT	INLET TEMPERATURES COLD	OUTLET TEMPERATURES HOT	OUTLET TEMPERATURES COLD	HEAT LOAD	OVERALL HEAT TRANSFER COEFFICIENT	AREA
1	1	2	413.33	150.00	250.00	360.00	.51E+07	.15E+03	462.
2	1	1	480.00	302.78	413.33	400.00	.21E+07	.15E+03	149.
3	2	1	323.81	100.00	150.00	302.78	.44E+07	.15E+03	873.
4	2	3	400.00	200.00	323.81	277.73	.19E+07	.15E+03	104.
5	ST	3	456.00	277.73	456.00	400.00	.30E+07	.20E+03	145.

TABLE 16. DESIGN TABLE FOR 5SP1

	TARGET	DESIGN
HEAT TRANSFER AREA	1400.	1730.
NUMBER OF HEAT EXCHANGERS ABOVE THE PINCH POINT BELOW THE PINCH POINT OVERALL	 5 0 5	 5 0 5
HOT UTILITY CONSUMPTION	.3020E+07	.3020E+07
COLD UTILITY CONSUMPTION	.0000	.0000
OPERATING COST	.3295E+05	.3295E+05
INVESTMENT COST	5448.	5383.
TOTAL COST	.3840E+05	.3834E+05

NUMBER OF INDEPENDENT HEAT LOAD LOOPS IS: 0

TABLE 17. PROPERTIES OF THE SOLUTION OF 5SP1

SAMPLE PROBLEM : 5SP1
INTRODUCED BY : Masso,Rudd [1]

AUTHOR(S)	REFERENCE #	TOTAL COST ($/yr)
Nishida,Liu,Lapidus	2	38219
Pho,Lapidus	13	38268
Lee,Masso,Rudd	20	38278
Kelahan,Gaddy	30	38316
Flower,Linnhoff	23	38268
Masso,Rudd	1	38268
Linnhoff,Flower	15	38268
HEXNET		38335

TABLE 18. COMPARISON TABLE FOR 5SP1

Nishida et.al. who considered stream splitting, proposed the optimal solution costing $23219/yr. Their own pricing was in fact $38713/yr since they had used 260 hr/yr as equipment down time and 767.5 Btu/lb as latent heat of steam. Later on, Linnhoff and Flower made a correction and computed the cost of this network with mostly accepted values; 380 hr/yr and 768 Btu/lb. What they had found was an annual cost of $38219.

The solutions presented by Pho and Lapidus, Lee et.al., Masso and Rudd, Linnhoff and Flower, and Kelahan and Gaddy are all identical.

Flower and Linnhoff presented five different networks costing between $38268 to $38550/yr by using their TC method.The solution developed by DESIGN is same as one of these networks and costs $38335/yr.

In this problem, the "tick-off" heuristic fails and selection of the hot and cold streams for the next match highly affects the total cost of the final network.

The deviation of the cost of DESIGN's solution from the optimal one is 0.18 per cent.

```
 ----------------------------------------------------------------------------
I                                                                            I
I                           STREAM DATA FOR 6SP1                             I
I____________________________________________________________________________I
I                                                                            I
I MINIMUM APPROACH TEMPERATURE:   20.00                                      I
I____________________________________________________________________________I
I NUMBERI  TYPE I TEMPERATURE I (*) HEAT I    HEAT    I       I              I
I   OF  I   OF  I_____________I CAPACITY I  TRANSFER  I PHASE I              I
I STREAMI STREAMI  IN  I  OUT I FLOW RATEI COEFFICIENTI CHANGEI   HEAT LOAD  I
I_______I_______I______I______I__________I____________I_______I______________I
I       I       I      I      I          I            I       I              I
I   1   I  HOT  I 440.0I 150.0I 28000.00 I 300.00000  I   NO  I  8120000.0000I
I_______I_______I______I______I__________I____________I_______I______________I
I       I       I      I      I          I            I       I              I
I   2   I  HOT  I 520.0I 300.0I 23800.00 I 300.00000  I   NO  I  5236000.0000I
I_______I_______I______I______I__________I____________I_______I______________I
I       I       I      I      I          I            I       I              I
I   3   I  HOT  I 390.0I 150.0I 33600.00 I 300.00000  I   NO  I  8064000.0000I
I_______I_______I______I______I__________I____________I_______I______________I
I       I       I      I      I          I            I       I              I
I   1   I  COLD I 100.0I 430.0I 16000.00 I 300.00000  I   NO  I -5280000.0000I
I_______I_______I______I______I__________I____________I_______I______________I
I       I       I      I      I          I            I       I              I
I   2   I  COLD I 180.0I 350.0I 32760.00 I 300.00000  I   NO  I -5569200.0000I
I_______I_______I______I______I__________I____________I_______I______________I
I       I       I      I      I          I            I       I              I
I   3   I  COLD I 200.0I 400.0I 26350.00 I 300.00000  I   NO  I -5270000.0000I
I_______I_______I______I______I__________I____________I_______I______________I
I                                                                            I
I               (*) in case of phase change  MASS FLOW RATE                  I
I____________________________________________________________________________I

         MINIMUM APPROACH TEMPERATURE: 20.00
         NUMBER OF SUBNETWORKS: 10
         PINCH TEMPERATURE HOT END:520.00
                          COLD END:500.00
         MINIMUM UTILITY HEATING:        .0000
         MINIMUM UTILITY COOLING: 5300800.0000
```

TABLE 19. STREAM DATA FOR 6SP1

```
 ---------------------------------------------------------------------------------------------------------
I                                                                                                         I
I                                    DESIGN TABLE FOR 6SP1.                                               I
I_________________________________________________________________________________________________________I
I     I NUMBER OF I     INLET     I    OUTLET     I         I  OVERALL   I          I
I     I  STREAM   I TEMPERATURESI TEMPERATURESI         I   HEAT     I          I
I HEX I___________I_____________I_____________I  HEAT   I TRANSFER   I   AREA   I
I  #  I HOT I COLDI  HOT I COLD I  HOT I COLD I  LOAD   ICOEFFICIENTI          I
I_____I_____I_____I______I______I______I______I_________I____________I__________I
I     I     I     I      I      I      I      I         I            I          I
I   1 I   2 I   1 I520.00I102.75I300.00I430.00I .52E+07I  .15E+03   I  255.    I
I_____I_____I_____I______I______I______I______I_________I____________I__________I
I     I     I     I      I      I      I      I         I            I          I
I   2 I   1 I   3 I440.00I200.00I251.79I400.00I .53E+07I  .15E+03   I  770.    I
I_____I_____I_____I______I______I______I______I_________I____________I__________I
I     I     I     I      I      I      I      I         I            I          I
I   3 I   3 I   2 I390.00I180.00I224.25I350.00I .56E+07I  .15E+03   I  882.    I
I_____I_____I_____I______I______I______I______I_________I____________I__________I
I     I     I     I      I      I      I      I         I            I          I
I   4 I   1 I   1 I251.79I100.00I250.21I102.75I .44E+05I  .13E+03   I  1.96    I
I_____I_____I_____I______I______I______I______I_________I____________I__________I
I     I     I     I      I      I      I      I         I            I          I
I   5 I   1 I  CW I250.21I100.00I150.00I180.00I .28E+07I  .15E+03   I  314.    I
I_____I_____I_____I______I______I______I______I_________I____________I__________I
I     I     I     I      I      I      I      I         I            I          I
I   6 I   3 I  CW I224.25I100.00I150.00I180.00I .25E+07I  .15E+03   I  353.    I
I_____I_____I_____I______I______I______I______I_________I____________I__________I
```

TABLE 20. DESIGN TABLE FOR 6SP1

```
 ------------------------------------------------------------------------------------------
I                                 I                         I                          I
I                                 I         TARGET          I          DESIGN          I
I_________________________________I_________________________I__________________________I
I                                 I                         I                          I
I  HEAT TRANSFER AREA             I          2090.          I          2577.           I
I_________________________________I_________________________I__________________________I
I  NUMBER OF HEAT EXCHANGERS      I                         I                          I
I          ABOVE THE PINCH POINT  I            0            I            0             I
I          BELOW THE PINCH POINT  I            6            I            6             I
I          OVERALL                I            6            I            6             I
I_________________________________I_________________________I__________________________I
I                                 I                         I                          I
I  HOT UTILITY CONSUMPTION        I          .0000          I          .0000           I
I_________________________________I_________________________I__________________________I
I                                 I                         I                          I
I  COLD UTILITY CONSUMPTION       I          .5301E+07      I          .5301E+07       I
I_________________________________I_________________________I__________________________I
I                                 I                         I                          I
I  OPERATING COST                 I          .2776E+05      I          .2776E+05       I
I_________________________________I_________________________I__________________________I
I                                 I                         I                          I
I  INVESTMENT COST                I          7332.          I          7247.           I
I_________________________________I_________________________I__________________________I
I                                 I                         I                          I
I  TOTAL COST                     I          .3510E+05      I          .3501E+05       I
I_________________________________I_________________________I__________________________I

      NUMBER OF INDEPENDENT HEAT LOAD LOOPS IS:                  0
```

TABLE 21. PROPERTIES OF THE SOLUTION OF 6SP1

SAMPLE PROBLEM : 6SP1
INTRODUCED BY : Lee,Masso,Rudd [20]

AUTHOR(S)	REFERENCE #	TOTAL COST ($/yr)
Nishida,Liu,Lapidus	2	35010
Linnhoff,Flower	15	35010
Lee,Masso,Rudd	20	37331
Flower,Linnhoff	23	35010
Pho,Lapidus	13	35657
Kelahan,Gaddy	30	35048
Ponton,Donaldson	21	35407
HEXNET		35010

TABLE 22. COMPARISON TABLE FOR 6SP1

The total cost of the network developed by DESIGN is cheaper than the networks synthesized by most of the previous investigators such as Lee et.al., Pho and Lapidus, and Ponton and Donaldson.The corresponding costs of these networks are $37331, $35657, and $35407/yr, respectively.Note that the total cost of the network obtained by Lee et.al. is given here as $37331/yr. This value was given incorrectly as $35108/yr by Lee et.al. and $35714/yr by Pho and Lapidus. Although a computational error in the work of Lee et.al. was found earlier by Pho and Lapidus, there still exists another computational error related with ΔT_{min} constraint.

The solution by Kelahan and Gaddy is not feasible since minimum approach temperature is 5.6 °C for their structure.

The network which is confirmed by DESIGN costs $35010/yr and is the definite optimum solution.

```
 ----------------------------------------------------------------------------------
I                                                                                  I
I                           STREAM DATA FOR 7SP1                                   I
I__________________________________________________________________________________I
I                                                                                  I
I MINIMUM APPROACH TEMPERATURE:    20.00                                           I
I__________________________________________________________________________________I
I NUMBERI  TYPE I TEMPERATURE I (*) HEAT I    HEAT      I       I                  I
I   OF  I   OF  I_____________I CAPACITY I  TRANSFER    I PHASE I                  I
I STREAMI STREAMI  IN   I  OUT I FLOW RATEI COEFFICIENTI CHANGEI     HEAT LOAD     I
I_______I_______I______I______I__________I____________I_______I__________________I
I       I       I      I      I          I            I       I                  I
I   1   I   HOT I 440.0I 150.0I 28000.00 I  300.00000 I  NO   I   8120000.0000I
I_______I_______I______I______I__________I____________I_______I__________________I
I       I       I      I      I          I            I       I                  I
I   2   I   HOT I 520.0I 300.0I 23800.00 I  300.00000 I  NO   I   5236000.0000I
I_______I_______I______I______I__________I____________I_______I__________________I
I       I       I      I      I          I            I       I                  I
I   3   I   HOT I 390.0I 150.0I 33600.00 I  300.00000 I  NO   I   8064000.0000I
I_______I_______I______I______I__________I____________I_______I__________________I
I       I       I      I      I          I            I       I                  I
I   1   I  COLD I 100.0I 430.0I 16000.00 I  300.00000 I  NO   I  -5280000.0000I
I_______I_______I______I______I__________I____________I_______I__________________I
I       I       I      I      I          I            I       I                  I
I   2   I  COLD I 180.0I 350.0I 32760.00 I  300.00000 I  NO   I  -5569200.0000I
I_______I_______I______I______I__________I____________I_______I__________________I
I       I       I      I      I          I            I       I                  I
I   3   I  COLD I 200.0I 400.0I 26350.00 I  300.00000 I  NO   I  -5270000.0000I
I_______I_______I______I______I__________I____________I_______I__________________I
I       I       I      I      I          I            I       I                  I
I   4   I  COLD I 350.0I 410.0I 19840.00 I  300.00000 I  NO   I  -1190400.0000I
I_______I_______I______I______I__________I____________I_______I__________________I
I                                                                                  I
I                  (*) in case of phase change  MASS FLOW RATE                     I
I__________________________________________________________________________________I

           MINIMUM APPROACH TEMPERATURE: 20.00
           NUMBER OF SUBNETWORKS: 11
           PINCH TEMPERATURE HOT END:520.00
                             COLD END:500.00
           MINIMUM UTILITY HEATING:          .0000
           MINIMUM UTILITY COOLING: 4110400.0000
```

TABLE 23. STREAM DATA FOR 7SP1

DESIGN TABLE FOR 7SP1

HEX #	NUMBER OF STREAM		INLET TEMPERATURES		OUTLET TEMPERATURES		HEAT LOAD	OVERALL HEAT TRANSFER COEFFICIENT	AREA
	HOT	COLD	HOT	COLD	HOT	COLD			
1	4	4	520.00	350.00	370.00	410.00	.12E+07	.15E+03	150.
2	2	1	520.00	177.15	264.98	430.00	.40E+07	.15E+03	303.
3	1	3	440.00	200.00	251.79	400.00	.53E+07	.15E+03	770.
4	3	2	390.00	180.00	224.25	350.00	.56E+07	.15E+03	882.
5	1	1	251.79	100.00	207.70	177.15	.12E+07	.15E+03	91.3
6	1	CW	207.70	100.00	150.00	180.00	.16E+07	.15E+03	295.
7	3	CW	224.25	100.00	150.00	180.00	.25E+07	.15E+03	353.

TABLE 24. DESIGN TABLE FOR 7SP1

	TARGET	DESIGN
HEAT TRANSFER AREA	2587.	2835.
NUMBER OF HEAT EXCHANGERS		
ABOVE THE PINCH POINT	0	0
BELOW THE PINCH POINT	7	7
OVERALL	7	7
HOT UTILITY CONSUMPTION	.0000	.0000
COLD UTILITY CONSUMPTION	.4110E+07	.4110E+07
OPERATING COST	.2184E+05	.2184E+05
INVESTMENT COST	8588.	8472.
TOTAL COST	.3042E+05	.3031E+05

NUMBER OF INDEPENDENT HEAT LOAD LOOPS IS: 0

TABLE 25. PROPERTIES OF THE SOLUTION OF 7SP1

SAMPLE PROBLEM : 7SP1
INTRODUCED BY : Masso,Rudd [1]

AUTHOR(S)	REFERENCE #	TOTAL COST ($/yr)
Linnhoff,Flower	15	30172
Ponton,Donaldson	21	30172
Pho,Lapidus	13	31700
Masso,Rudd	1	34376
HEXNET		30309

TABLE 26. COMPARISON TABLE FOR 7SP1

7SP1 has been solved by Masso and Rudd, Pho and Lapidus, Ponton and Donaldson and Linnhoff and Flower.

Pho and Lapidus claimed an annual cost of $30433 for their solution owing to an error in cooling water costs.The true cost for their solution is approximately $31700/yr.

Ponton and Donalson did not present a network but reported finding one (by means of their H/2H algorithm) costing $30172/yr.It seems quite certain that they found the same structure with Linnhoff and Flower.

The solution by DESIGN differs from this optimal cost by 0.45 per cent and is the only solution which employs stream splitting.

```
I---------------------------------------------------------------------------------------I
I                                 STREAM DATA FOR 7SP2                                  I
I_______________________________________________________________________________________I
I                                                                                       I
I MINIMUM APPROACH TEMPERATURE:    20.00                                                I
I_______________________________________________________________________________________I
I NUMBERI  TYPE I TEMPERATURE I (*) HEAT I    HEAT     I       I                        I
I  OF   I   OF  I_____________I CAPACITY I  TRANSFER   I PHASE I                        I
I STREAMI STREAMI  IN  I  OUT I FLOW RATEI COEFFICIENTI CHANGEI     HEAT LOAD          I
I_______I_______I______I______I__________I_____________I_______I________________________I
I       I       I      I      I          I             I       I                        I
I   1   I   HOT I 590.0I 400.0I 23760.00 I  300.00000  I   NO  I      4514400.0000I
I_______I_______I______I______I__________I_____________I_______I________________________I
I       I       I      I      I          I             I       I                        I
I   2   I   HOT I 471.0I 200.0I 15770.00 I  300.00000  I   NO  I      4273670.0000I
I_______I_______I______I______I__________I_____________I_______I________________________I
I       I       I      I      I          I             I       I                        I
I   3   I   HOT I 533.0I 150.0I 13200.00 I  300.00000  I   NO  I      5055600.0000I
I_______I_______I______I______I__________I_____________I_______I________________________I
I       I       I      I      I          I             I       I                        I
I   1   I  COLD I 200.0I 400.0I 16000.00 I  300.00000  I   NO  I     -3200000.0000I
I_______I_______I______I______I__________I_____________I_______I________________________I
I       I       I      I      I          I             I       I                        I
I   2   I  COLD I 100.0I 430.0I 16000.00 I  300.00000  I   NO  I     -5280000.0000I
I_______I_______I______I______I__________I_____________I_______I________________________I
I       I       I      I      I          I             I       I                        I
I   3   I  COLD I 300.0I 400.0I 41280.00 I  300.00000  I   NO  I     -4128000.0000I
I_______I_______I______I______I__________I_____________I_______I________________________I
I       I       I      I      I          I             I       I                        I
I   4   I  COLD I 150.0I 280.0I 26240.00 I  300.00000  I   NO  I     -3411200.0000I
I_______I_______I______I______I__________I_____________I_______I________________________I
I                                                                                       I
I                   (*) in case of phase change  MASS FLOW RATE                         I
I_______________________________________________________________________________________I

            MINIMUM APPROACH TEMPERATURE: 20.00
            NUMBER OF SUBNETWORKS: 12
            PINCH TEMPERATURE HOT END:120.00
                             COLD END:100.00
            MINIMUM UTILITY HEATING: 2175530.0000
            MINIMUM UTILITY COOLING:           .0000
```

TABLE 27. STREAM DATA FOR 7SP2

```
I---------------------------------------------------------------------------------------I
I                                                                                       I
I                              DESIGN TABLE FOR 7SP2                                    I
I_______________________________________________________________________________________I
I     I NUMBER OF I     INLET     I    OUTLET     I         I  OVERALL    I             I
I     I  STREAM   I TEMPERATURESI TEMPERATURESI         I   HEAT      I             I
I HEX I___________I_____________I_____________I  HEAT   I TRANSFER    I    AREA     I
I  #  I HOT I COLDI  HOT I COLD I  HOT I COLD I  LOAD   ICOEFFICIENTI             I
I_____I_____I_____I______I______I______I______I_________I_____________I_____________I
I     I     I     I      I      I      I      I         I             I             I
I   1 I   3 I   2 I533.00I100.00I150.00I415.98I .51E+07I   .15E+03   I   428.      I
I_____I_____I_____I______I______I______I______I_________I_____________I_____________I
I     I     I     I      I      I      I      I         I             I             I
I   2 I   2 I   4 I416.31I150.00I200.00I280.00I .34E+07I   .15E+03   I   264.      I
I_____I_____I_____I______I______I______I______I_________I_____________I_____________I
I     I     I     I      I      I      I      I         I             I             I
I   3 I   1 I   1 I534.68I200.00I400.00I400.00I .32E+07I   .15E+03   I   129.      I
I_____I_____I_____I______I______I______I______I_________I_____________I_____________I
I     I     I     I      I      I      I      I         I             I             I
I   4 I   2 I   3 I471.00I300.00I416.31I320.89I .86E+06I   .15E+03   I   43.4      I
I_____I_____I_____I______I______I______I______I_________I_____________I_____________I
I     I     I     I      I      I      I      I         I             I             I
I   5 I   1 I   3 I590.00I320.89I534.68I352.73I .13E+07I   .15E+03   I   38.9      I
I_____I_____I_____I______I______I______I______I_________I_____________I_____________I
I     I     I     I      I      I      I      I         I             I             I
I   6 I  ST I   2 I456.00I415.98I456.00I430.00I .22E+06I   .20E+03   I   34.5      I
I_____I_____I_____I______I______I______I______I_________I_____________I_____________I
I     I     I     I      I      I      I      I         I             I             I
I   7 I  ST I   3 I456.00I352.73I456.00I400.00I .20E+07I   .20E+03   I   126.      I
I_____I_____I_____I______I______I______I______I_________I_____________I_____________I
```

TABLE 28. DESIGN TABLE FOR 7SP2

	TARGET	DESIGN
HEAT TRANSFER AREA	1047.	1064.
NUMBER OF HEAT EXCHANGERS		
ABOVE THE PINCH POINT	7	7
BELOW THE PINCH POINT	0	0
OVERALL	7	7
HOT UTILITY CONSUMPTION	.2176E+07	.2176E+07
COLD UTILITY CONSUMPTION	.0000	.0000
OPERATING COST	.2408E+05	.2408E+05
INVESTMENT COST	5595.	4549.
TOTAL COST	.2967E+05	.2863E+05

NUMBER OF INDEPENDENT HEAT LOAD LOOPS IS: 0

TABLE 29. PROPERTIES OF THE SOLUTION OF 7SP2

SAMPLE PROBLEM : 7SP2
INTRODUCED BY : Masso,Rudd [1]

AUTHOR(S)	REFERENCE #	TOTAL COST ($/yr)
Linnhoff,Flower	15	28258
Pho,Lapidus	13	28518
Masso,Rudd	1	28628
HEXNET		28627

TABLE 30. COMPARISON TABLE FOR 7SP2

Problem 7SP2 was introduced by Masso and Rudd as one for which the heat recovery situation is very easy with many feasible structures that employ minimum number of units and achieve maximum energy recovery.

The solution by Masso and Rudd costs $28628/yr.Though this price is almost the same as DESIGN's, the networks are very different from each other.

Pho and Lapidus claimed to have found a solution costing $28518/yr, but the structure they presented is not feasible since at least two streams miss their target temperatures.

The optimal network by Linnhoff and Flower can not be produced by Pinch Technique since this method locates the heaters and coolers after all possible heat exchange between process streams is performed. Any cold streams above the pinch and/or hot streams below the pinch which can not reach their target temperatures by heat exchange with the other process streams are matched with utility streams.The structure by Linnhoff and Flower includes a steam heater located without obeying this order so, can not be developed by Pinch method though it thermodynamically and economically feasible.

STREAM DATA FOR 10SP1

MINIMUM APPROACH TEMPERATURE: 20.00

NUMBER OF STREAM	TYPE OF STREAM	TEMPERATURE IN	TEMPERATURE OUT	(*) HEAT CAPACITY FLOW RATE	HEAT TRANSFER COEFFICIENT	PHASE CHANGE	HEAT LOAD
1	HOT	320.0	200.0	16670.00	300.00000	NO	2000400.0000
2	HOT	480.0	280.0	20000.00	300.00000	NO	4000000.0000
3	HOT	440.0	150.0	28000.00	300.00000	NO	8120000.0000
4	HOT	520.0	300.0	23800.00	300.00000	NO	5236000.0000
5	HOT	390.0	150.0	33600.00	300.00000	NO	8064000.0000
1	COLD	140.0	320.0	14450.00	300.00000	NO	-2601000.0000
2	COLD	240.0	431.0	11530.00	300.00000	NO	-2202230.0000
3	COLD	100.0	430.0	16000.00	300.00000	NO	-5280000.0000
4	COLD	180.0	350.0	32760.00	300.00000	NO	-5569200.0000
5	COLD	200.0	400.0	26350.00	300.00000	NO	-5270000.0000

(*) in case of phase change MASS FLOW RATE

```
MINIMUM APPROACH TEMPERATURE: 20.00
NUMBER OF SUBNETWORKS: 17
PINCH TEMPERATURE HOT END:520.00
                  COLD END:500.00
MINIMUM UTILITY HEATING:          .0000
MINIMUM UTILITY COOLING: 6497970.0000
```

TABLE 31. STREAM DATA FOR 10SP1

DESIGN TABLE FOR 10SP1

HEX #	NUMBER OF STREAM HOT	NUMBER OF STREAM COLD	INLET TEMPERATURES HOT	INLET TEMPERATURES COLD	OUTLET TEMPERATURES HOT	OUTLET TEMPERATURES COLD	HEAT LOAD	OVERALL HEAT TRANSFER COEFFICIENT	AREA
1	4	2	520.00	240.00	427.47	431.00	.22E+07	.15E+03	111.
2	2	3	480.00	180.00	280.00	430.00	.40E+07	.15E+03	370.
3	3	5	440.00	200.00	251.79	400.00	.53E+07	.15E+03	770.
4	4	4	427.47	257.39	300.00	350.00	.30E+07	.15E+03	347.
5	5	1	390.00	140.00	312.59	320.00	.26E+07	.15E+03	153.
6	5	4	312.59	180.00	237.13	257.39	.25E+07	.15E+03	301.
7	1	3	320.00	100.00	243.22	180.00	.13E+07	.15E+03	60.3
8	1	CW	243.22	100.00	200.00	180.00	.72E+06	.15E+03	59.9
9	3	CW	251.79	100.00	150.00	180.00	.29E+07	.15E+03	315.
10	5	CW	237.13	100.00	150.00	180.00	.29E+07	.15E+03	365.

TABLE 32. DESIGN TABLE FOR 10SP1

	TARGET	DESIGN
HEAT TRANSFER AREA	2684.	2851.
NUMBER OF HEAT EXCHANGERS		
ABOVE THE PINCH POINT	0	0
BELOW THE PINCH POINT	10	10
OVERALL	10	10
HOT UTILITY CONSUMPTION	.0000	.0000
COLD UTILITY CONSUMPTION	.6498E+07	.6498E+07
OPERATING COST	.3452E+05	.3452E+05
INVESTMENT COST	.1053E+05	9781.
TOTAL COST	.4505E+05	.4430E+05

NUMBER OF INDEPENDENT HEAT LOAD LOOPS IS: 0

TABLE 33. PROPERTIES OF THE SOLUTION OF 10SP1

SAMPLE PROBLEM : 10SP1
INTRODUCED BY : Pho,Lapidus [13]

AUTHOR(S)	REFERENCE #	TOTAL COST ($/yr)
Linnhoff,Flower	15	43934
Pho,Lapidus	13	44158
Nishida,Liu,Lapidus	2	43984
HEXNET		44301

TABLE 34. COMPARISON TABLE FOR 10SP1

The most complex example in the literature is 10SP1 which was first presented by Pho and Lapidus. The optimal solution, costing $43934/yr is obtained by Linnhoff and Flower. The network synthesized by DESIGN costs $44301/yr and is only 0.83 per cent more expensive than the optimal one.

None of the two solutions in the above table are similar to each other, since they all follow different paths which are numereous when dealing with such big problems.

Finally, two more problems will be mentioned here. TC1 [15] and TC3 [25] are solved by HEXNET and DESIGN and the networks obtained are exactly the same as the ones given in related papers.

CHAPTER V

CONCLUSIONS

This chapter is devoted to conclusions and four suggestions to improve the programs developed during this study.

5.1 Conclusions

Two separate computer programs, HEXNET and DESIGN, are developed in this study.The former computes the targets by using the methods that are discussed in Chapter II.As a summary these targets can be listed as follows:

(i) Minimum utility consumption
(ii) Minimum number of heat exchangers
(iii) Minimum heat transfer area.

Consistency of HEXNET is checked by running several problems abstracted from literature and no disagreement is observed in the calculation of targets (i) and (ii).As it is not possible to determine an exact target for heat transfer area in case of match dependent heat transfer coefficients, an approximation had to be used. This approximation is said to be accurate within 10 per cent [27], so the user of HEXNET should always consider the limits of confidence. However, this uncertainity has almost no meaning since the third target is usually approached but not reached by the optimal solutions [12].

One superiority of HEXNET is its ability to handle the problems in which one or more streams undergo a phase change. Such streams are not considered by most of the earlier algorithms and limited number of examples are available in literature.

TARGET II is a software package which is recently developed by Linnhoff March Process Integration Consultants and determines utility (hot and cold) requirements of a network [31]. A phase change problem can be solved with this package by assuming a fictitious temperature change of 0.1 °F in the supply temperature of the stream either condensing or vaporising.Another recent algorithm [24] assumes this value as being 1 K.

When handling phase change problems, HEXNET does not make any assumptions.The target and supply temperatures of such streams are kept equal throughout computation.Comparison of the results of two procedures could not be possible due to absence of examples in literature and the failure in supplying the package mentioned above.

Another superiority of HEXNET is the option related with the minimum approach temperature.The user may choose a predetermined ΔT_{min} or let the program to compute the optimal one.In case of second choice, an outer loop employing Fibonacci search is included and by evaluating the total costs of several networks (each with a different ΔT_{min}), optimal approach temperature is determined.Thus, the user has a chance to investigate the effects of that parameter on his objective.

The second computer program developed in this study is called DESIGN and it performs the synthesis of networks which satisfy targets (i) and (ii).The first target is reached by developing two separate designs, one above and the other below the pinch.This procedure does not allow any heat transfer across the pinch and hence yields a solution with minimum utility consumption.The networks synthesized by DESIGN also include minimum number of heat exchanger units ; satisfying the second target.As mentioned earlier, a method to reach such a solution is to maximise the heat loads of heat exchangers or in other words to carry at least one of the streams from its supply to target temperature at each match.An apparent disadvantage of DESIGN is the fact that where full heat recovery is difficult to achieve, i.e., where more than the minimum number of units have to be used, the program may yield no solution.Few problems in literature have these characteristics.

Generally, the number of possible solutions to a problem is more than one.The reason of this is straightforward.During the unit by unit generation of a network, one may encounter alternative paths to follow (e.g. thermodynamic constraints may allow a cold(hot) stream to be matched with one of the two different hot(cold) streams). The path followed at such a decision node, certainly affects the remaining configuration of the network. In practice, when this situation is encountered, the engineer selects the solution that fulfills the requirements of his process dependent constraints. While programming DESIGN, no constraints (excluding thermodynamic ones) are taken into account. So, a heuristic approach was necessary to define the hot and the cold side fluids of the next match. The approach is explained in details elsewhere (see Chapter III). Here the success of this application will be pointed out.

Chapter IV includes the feasible solutions of nine standard problems.All of the results contain minimum number of units and achieve maximum energy recovery.For five of them, optimal solutions are confirmed by DESIGN.For the others, the maximum deviation from the optimal cost is 1.3 per cent which is encountered in case of 7SP2.As it has been already mentioned, the heat recovery situation is very easy for this problem and one can develop several networks satisfying targets (i) and (ii).

Other deviations are in the range of 0.18 - 0.83 per cent. These differences may be due to different stream or design data which are not indicated clearly in most of the sources.As it is observed by Nishida et.al. [2], a small difference of 0.5 Btu/lb. in the latent heat of steam used will lead to a corresponding difference in the total cost of the network of the order of $20 to $80/yr.

5.2 Recommendations

Heat Integration has become an important subject in chemical engineering practice since energy costs have increased rapidly for the last decades. It should be priorly accepted that, applying an underdeveloping technique to industrial processes; each showing a variety of difficulties and problems within itself, is a hard project to handle. The recommendation part of this study shows some of the major steps to be taken in order to satisfy some particular needs of industrial problems.

The following suggestions may be realised by adding new subprograms to the existing files. However, computer programs developed in this work are so arranged that it is also possible to generate new programs which can stay in contact with the existing ones by proper file operations.

The first suggestion is related with the constraints. Designers are always faced with many more constraints than purely thermodynamic ones when designing heat exchanger networks. The forbidden matches constitute a major part of such constraints. There are many reasons why a designer might want to forbid a match between any given pair of streams, for example corrosion and safety problems, long pipe runs required, or controllability. Imposing a forbidden match might or might not affect the possible energy recovery of the network. In general heat exchanger networks, the problem of deciding whether or not a forbidden match constraint will affect the energy target, and if so by how much, is a difficult one. However, there are some algorithms that rigorously solve this problem [19].

When it comes to a design method for forbidden-match problems, an equivalent of the pinch design method has not been developed yet. At the moment, the best way to approach the problem is probably to produce an "unconstrained" maximum energy recovery design by the pinch design method, and then to modify it in the light of the constraint and the modified energy target [4].

Secondly, we look at the constraint of imposed matches. For reasons of operability (e.g. start up and control), layout and in order to re-use existing units in "revamps", the designer may want to include a certain match in his design. The same question arised above, is also valid in case of imposed matches. Remaining problem analysis which is explained in subsection 2.2.3.3, is a powerful tool to determine if extra utility requirement is necessary. Implementation of these constraints to a computer program seems to be a difficult task unless algorithms LP, MILP, NLP are employed. Problem Table method is not a suitable procedure to determine energy target under such constraints, since this method is based upon formation of superstreams and no exact solution can be proposed if two streams which would not be matched take place in the same interval or the placement of a heater or cooler on a certain stream at a certain temperature is required for some reasons.

The second suggestion is related with the usage of multiple utilities. This application as explained in section 2.2.5, is more realistic than one hot/one cold utility case. During the development of a computer program ,it is thought that, the major problem that may arise, is to determine where to start the design since multiple utilities often introduce multiple pinch points. The recommendation is to design away from the most constrained pinch first (see section 2.2.5.2). In any case,it may be a hard work to "teach" a computer how to determine the most constrained pinch. As it is the case in almost all steps of this work, one should include numerous responses to a variety of possibilities which differ from one problem to an other.

Third suggestion is about the development of a comprehensive loop-breaking evolutionary method for energy relaxation. As it is indicated in section 2.2.4, this is the only way to determine capital/energy trade-offs. It is thought to be beneficial to define a step by step procedure for reducing units at minimum energy sacrifice.

* Identify a loop (across the pinch).

The problem that may arise at this step is the identification of complex loops. Such loops generally occur when the streams are splitted in order to reach maximum energy recovery design. The only way to trace out a loop seems to be a trial-error procedure.

* Break the loop by subtracting and adding heat load X.

As mentioned by Linnhoff et.al. [4] it is not possible a priori to say the removal of which unit will lead to the smallest energy relaxation. This should also necessitate some trials before reaching a final solution.

* Recalculate network temperatures and identify the ΔT_{min} violations.
* Find a relaxation path and formulate $T=f(X)$.

Now, one should exploit a path through the network. Complex paths may also occur and trial-error procedure seems to be the only way to solve such a problem. Begining from one of the heaters, one must trace-out all possible paths which must be suitable for energy relaxation and end by reaching a cooler.

* Restore ΔT_{min}.
* Calculate the capital and energy costs of the new configuration.
* If exist, repeat the same procedure for other loops.

A final suggestion is about the computer implementation of retrofit design procedure. Since many existing plants need heat integration to save energy, special emphasis should be placed on this task. Blow, a proposal for the development of such a program is given.

HEXNET may aid to the programmer by defining the targets and pinch temperature. The topology of the network to be improved should be read from a data file. Knowing the topology and pinch temperature, one can easily identify the cross-pinch exchangers. This constitutes the first step of the procedure summarised in section 2.2.6.3. While completing the network, a sub-program similar to the one utilised by DESIGN (or may be the DESIGN itself!) is necessary. Here, it is thought that, the programmer will face a difficulty in re-using existing units. It should be tedius work to make use of flexibilities in order to fit old exchangers into new duties.

APPENDIX A

FIBONACCI SEARCH

Appendix A summarizes the basic principles of the search technique which is employed in this study to determine the optimal approach temperature.More information can be obtained from [11].

Suppose that we place two points x_1 and x_2 symmetrically within the interval $a \le x \le b$, as shown in line (I) of Figure A.1.If $y(x_2) > y(x_1)$, then we form a new search interval $x_1 \le x \le b$, as line (II) of Figure A.1. We could, if we wish, place two new search points within the new interval and repeat the above search procedure.Instead, however, let us take advantage of the fact that x_2 has already been placed in our new search interval from the previous search interval, and that $y(x_2)$ has already been evaluated.Therefore, let us place only one new search point x_3 within our new interval, locating it symmetrically with respect to x_2.The arrangement of the search points within the new search interval is shown in line (III) of Figure A.1.Notice that by locating the search points symmetrically within any interval we shall always have subintervals of the same length, regardless of which search point yields the

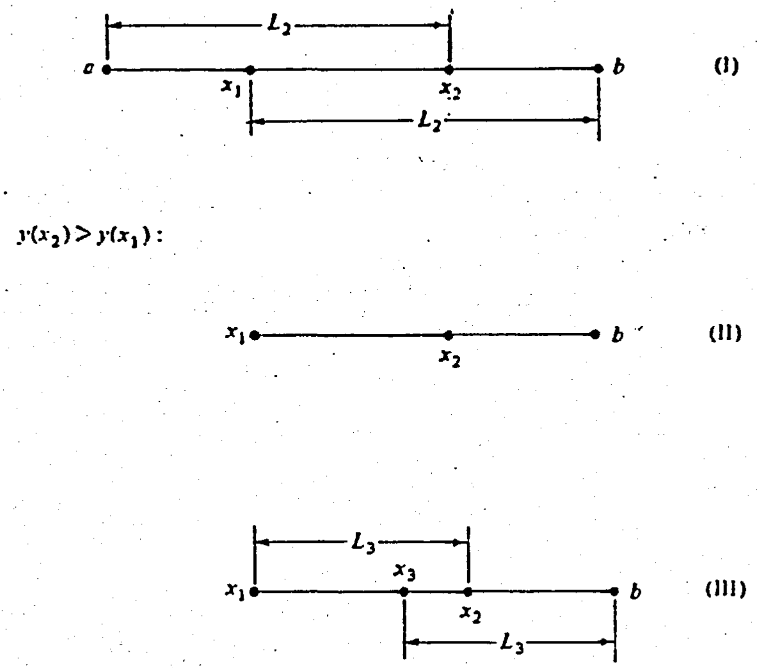


Figure A.1- Search point arrangement in a Fibonacci Search [11]

maximum;i.e.,

$$(x_2-x_1)=(b-x_2)=L_2. \tag{A-1}$$

Observe also that the search points rapidly move toward each other in successive search intervals.

Let us now require that L_n, the interval of uncertainty which results from the sequential placement of n search points, be minimized.We have already seen that the last two search points x_{n-1} and x_n must be symmetrically spaced and a distance ϵ apart within the last search interval, as in line (III) of Figure A.2.If in previous search interval $y(x_{n-1}) > y(x_{n-2})$, however, then x_{n-2} forms the new boundary of the last search interval, and x_{n-1} appears within the last search interval.This is shown in lines (II) and (III) in Figure A.2.

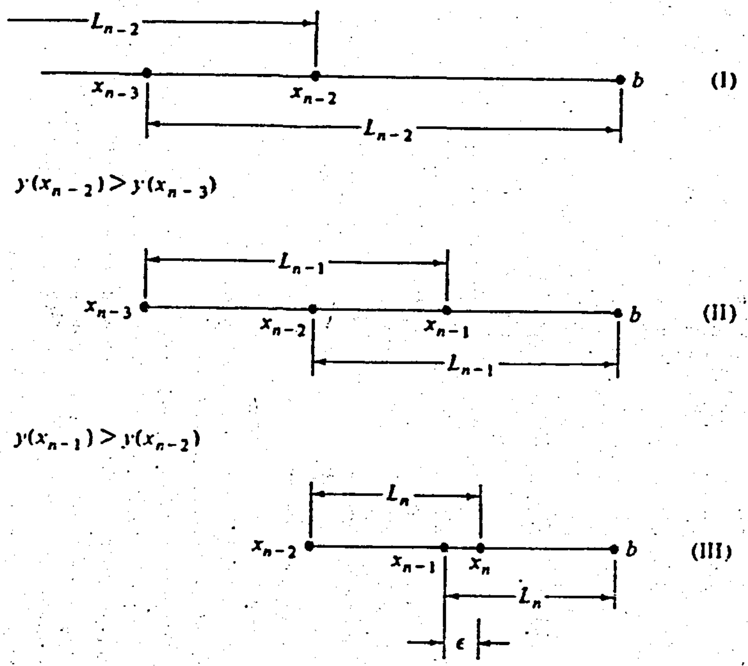


Figure A.2- Sequence of uncertainty intervals in Fibonacci Search [11]

Notice that the interval of uncertainty L_{n-1} becomes equal to $(b-x_{n-2})$, the new search interval.Hence we can write

$$L_n = \frac{(b - x_{n-2} + \epsilon)}{2} \qquad \text{(A-2)}$$

or

$$L_n = \frac{(L_n + \epsilon)}{2} \qquad \text{(A-3)}$$

Notice also that the second-last search interval (i.e., line (II), Figure A.2) can be written

$$(b-x_{n-3}) = (b-x_{n-1}) + (x_{n-1}-x_{n-3}), \qquad \text{(A-4)}$$

which, from Figure A.2 can be expressed as

$$(b-x_{n-3}) = L_n + L_{n-1}. \qquad \text{(A-5)}$$

However, from line (I) of Figure A.2 we can see that $(b-x_{n-3})$, the second-last search interval, is simply equal to L_{n-2} providing $y(x_{n-2}) > y(x_{n-3})$.Thus we have shown that

$$L_{n-2} = L_{n-1} + L_n, \qquad \text{(A-6)}$$

which can be generalized to read

$$L_i = L_{i+1} + L_{i+2}, \quad i= 1,2,\ldots.,n-2. \qquad \text{(A-7)}$$

The arguments that led to the above equations are not dependent upon which of the two search points in a given search interval yields the greater value for y. In Figure A.2, for example, we could have interchanged the positions of x_{n-2} and x_{n-3} in line (I), and, again working our way back from the final interval, obtained Equations A-3 and A-7. All that we require for Equations A-3 and A-7 to be valid are the symmetrical placement of the search points within each search interval and the minimum separation of the search points within the last search interval.

Combining Equations A-3 and A-7 to eliminate L_{n-1} gives

$$L_{n-2} = 3L_n - \epsilon. \qquad \text{(A-8)}$$

By successively applying Equation A-7 we can obtain

$$L_{n-3} = 5L_n - 2\epsilon, \qquad \text{(A-9)}$$

$$L_{n-4} = 8L_n - 3\epsilon, \qquad \text{(A-10)}$$

$$L_{n-k} = F_{k+1}L_n - F_{k-1}\epsilon. \qquad \text{(A-11)}$$

The coefficients F_{k+1} and F_{k-1} can be generated by the recurrence formula

$$F_{k+1} = F_k + F_{k-1}, \quad k=1,2,3,\ldots, \qquad \text{(A-12)}$$

providing $F_0 = F_1 = 1$. In other words, each coefficient is formed by adding together the two previous coefficients. The sequence of numbers so formed is known as Fibonacci number sequence.The first 40 Fibonacci numbers are shown in Table A-1.

TABLE A-1. COMPILATION OF FIBONACCI NUMBERS

n	F_n	n	F_n
0	1	21	17,711
1	1	22	28,657
2	2	23	46,368
3	3	24	75,025
4	5	25	121,393
5	8	26	196,418
6	13	27	317,811
7	21	28	514,229
8	34	29	832,040
9	55	30	1,346,269
10	89	31	2,178,309
11	144	32	3,524,578
12	233	33	5,702,887
13	377	34	9,277,465
14	610	35	14,930,352
15	987	36	24,157,817
16	1,597	37	39,088,169
17	2,584	38	63,245,986
18	4,181	39	102,334,155
19	6,765	40	165,580,141
20	10,946		

Consider the special case of Equation A-11 when k=n-1.We have

$$L_1 = F_n L_n - F_{n-2}\epsilon \qquad \text{(A-13)}$$

or

$$L_n = \frac{1}{F_n} L_1 + \frac{F_{n-2}}{F_n}\epsilon . \qquad \text{(A-14)}$$

Letting L_1 represents the length of the original search interval, Equation A-14 allows us to determine the interval of uncertainty remaining after the placement of n Fibonacci search points.The interval of uncertainty is reduced to less than 1 per cent of the original search interval for n=11, as compared to n=14 for a dichotomous search.

Once a Fibonacci search has been started, it is a simple matter to continue the placement of successive search points becouse of the symmetry that we require within each interval.The question remains as to the placement of the first two search points.We can answer this question by considering the relationship between L_1 and L_2.

If we evaluate Equation A-11 for the case of k=n-2, we obtain

$$L_2 = F_{n-1}L_n - F_{n-3}\epsilon. \qquad (A-15)$$

Combining this result with Equation A-13 to eliminate L_n gives

$$L_2 = \frac{F_{n-1}}{F_n} L_1 + \frac{F_{n-1}F_{n-2} - F_nF_{n-3}}{F_n} \epsilon, \qquad (A-16)$$

which can be written as

$$L_2 = \frac{F_{n-1}}{F_n} L_1 + \frac{(-1)^n}{F_n} \epsilon. \qquad (A-17)$$

Thus from Equation A-17 we can compute L_2 once we specify the total number of search points n and a value for ϵ.To begin a Fibonacci search within an interval L_1 = (b-a), we simply locate x_1 a distance of L_2 units from b, and x_2 is placed L_2 units from a.

It should be emphasized that the placement of the first two search points is based upon the condition that L_n, the interval of uncertainty remaining after n search points have been explored, is to be minimized.If n=2, the Fibonacci search simply reduces to a symmetrical two-point search, which minimizes L_2. When n=3, we ask if the search interval $L_2=(b-x_1)$ can be reduced, with x_2 and x_3 still symmetric in L_2 and separated by the minimum distance ϵ. For this to be so, x_1, and consequently x_2, must be located closer to the center of $L_1=(b-a)$. Thus x_2 would appear in a different location in $L_2=(b-x_1)$. Locating x_3 symmetrically in L_2, we would not have x_2 and x_3 separated by ϵ, which violates our original premise and either makes $y(x_2)$ and $y(x_3)$ indistinguishable or else increases L_3. Hence for n=3 we see that the Fibonacci search does indeed minimize the remaining interval of uncertainty. We can continue this type of logic for higher n if we wish, and thus we show by induction that the Fibonacci search technique minimizes L_n.

Let us now consider what happens when ϵ is allowed to vanish. With this condition the last two search points will coincide, and L_n will equal $L_{n-1}/2$. From Equation A-14, we have, for $\epsilon=0$,

$$L_n = \frac{1}{Fn} L_1. \qquad \text{(A-18)}$$

Since $x_n = x_{n-1}$, however, we obtain L_n with only (n-1), rather than n, search points.

REFERENCES

[1] Masso, A.H., and D.F.Rudd, AIChE J., 15, 9-16 (1969).

[2] Nishida, N., Y.A.Liu, and L.Lapidus, AIChE J., 23, 77-93 (1977).

[3] Linnhoff, B., D.R.Mason, and I.Wardle, Computers and Chem. Eng., 3, 295-302 (1979).

[4] Linnhoff, B., et.al., User Guide on Process Integration for the Efficient Use of Energy, Institution of Chemical Engineers, London, 1982.

[5] Boland, D., and B.Linnhoff, The Chemical Engineer, 222-228 (1979).

[6] Linnhoff, B., and J.A.Turner, The Chemical Engineer, 742-746 (1980).

[7] Linnhoff, B.,and J.A.Turner, Chem. Eng., 88, 56-70 (1981).

[8] Linnhoff, B., and D.R.Vredeveld, Chem. Eng. Prog., 80, 33-40 (1984).

[9] Linnhoff, B.,and W.D.Witherell, Oil and Gas J., 84, 54-65, (1986).

[10] Floudas, C.A., A.R.Ciric, and I.E.Grossmann, AIChE J., 32, 276-290 (1986).

[11] Gottfried, B.S., and J.Weisman, Introduction to Optimization Theory, Perentice-Hall, Inc., New Jersey, 1973.

[12] Nishida, N.,G.Stephanopoulos, and A.W.Westerberg, AIChE J., 27, 321-351 (1981).

[13] Pho, T.K., and L.Lapidus, AIChE J., 19, 1182-1189 (1973).

[14] Nishida, N., S.Kobayashi, and A.Ichikawa, Chem. Eng. Sci., 26, 1841-1856 (1971).

[15] Linnhoff, B., and J.R.Flower, AIChE J.,24, 633-654 (1978).

[16] Grossmann, I.E., and R.W.H.Sargent, AIChE J., 24,

1021-1028 (1978).

[17] Rathore, R.N.S., and G.J.Powers, Ind. Eng. Chem. Process Design Development, 14, 175-181 (1975).

[18] Umeda, T., J.Itoh, and K.Shiroko, Chem. Eng. Prog., 74, 70-76 (1978).

[19] Cerda, J., A.W.Westerberg, D.Mason, and B.Linnhoff, Chem. Eng. Sci., 38, 373-387 (1983).

[20] Lee, K.F., A.H.Masso, and D.F.Rudd, I & EC Fundamentals, 9, 48-58 (1970).

[21] Ponton, J.W., and R.A.B.Donaldson, Chem. Eng. Sci., 29, 2375-2377 (1974).

[22] Kobayashi, S., T.Umeda, and A.Ichikawa, Chem. Eng. Sci., 26, 1367-1830 (1971).

[23] Flower, J.R., and B.Linnhoff, AIChE J., 26, 1-9 (1980).

[24] Duran, M.A.,and E.Grossmann, AIChE J., 32, 123-138 (1986).

[25] Linnhoff, B.,and E.Hindmarsh, Chem. Eng. Sci., 38, 745-763 (1983).

[26] Hindmarsh, E., D.Boland, and D.W.Townsend, Chem. Eng., 92, 38-47 (1985).

[27] Tjoe, T.N., and B.Linnhoff, Chem. Eng., 93, 47-60 (1986).

[28] Townsend, D.W., and B.Linnhoff, AIChE J., 29, 742-771 (1983).

[29] Jones, D.A., A.N.Yilmaz, and B.E.Tilton, Chem. Eng. Prog., 82, 28-33 (1986).

[30] Kelahan, R.C., and J.L.Gaddy, AIChE J.,23, 816-822 (1977).

[31] CACHE Corporation, User's Guide for Target II, Texas,1987.