SYNTHESIS OF OPTIMAL HEAT EXCHANGER NETWORKS

A THESIS SUBMITTED IN FULFILLMENT
OF THE REQUIREMENT FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

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awarded 30.8.89

April 1988

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TO MY PARENTS

for inspiring, encouraging and sustaining

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Nomenclature

a	cost coefficient
A_{min}	minimum area target of a heat exchanger network (m^2)
A_s	area of a shell (m^2)
A_u	area of a unit (m^2)
b	cost exponent
c	heat exchanger cost per unit area
c_p	heat capacity (kW/kg K)
ccf	criss-cross factor
C_I	installation cost ($)
C_k	the set of all cold streams present in interval k
C_p	mass heat capacity flowrate (kW/K)
C_s	total annual capital cost based on the area of a shell ($)
C_t	total-capital cost ($)
C_u	total annual capital cost based on the area of a unit ($)
C_{steam}	steam cost ($/kg)
$C_{utility}$	annual cost of utility
C_{water}	cooling water cost ($/kg)
CP_L	larger C_p of the two streams associated with a match
CTD	corrected temperature difference
EC	energy consumption (kW)
EMAT	exchanger minimum approach temperature (K)
EP	energy penalty function (kW)
F	freedom of an exchanger

F_k	heat cascade from temperature interval k to k+1
F_t	LMTD correction factor
h	film heat transfer coefficient (kW/m^2 K)
H_k	the set of all hot streams present above interval k
HRAT	heat recovery approach temperature (K)
i	rate of return (annual profit/capital invested)
IM	the set of imposed matches
L	number of loops in a network
L_{max}	maximum number of loops present in a network
l_s	latent heat of steam at pressure p_s (kW/kg)
m	constant
M	years over which the fixed cost is amortized
n	constant
N_{cold}	total number of cold streams
$N_{constraint}$	total number of constraints
N_{hot}	total number of hot streams
N_{nodes}	number of branches
N_{pipes}	number of pipes
N_{shell}	number of shells
N_{stream}	total number of streams
N_{unit}	number of units
OM	the set of all other matches
P	thermal effectiveness
p_s	stream pressure (Pa)
Q	enthalpy of any stream (kW)
Q_c	total cold utility used (kW)
Q_{cmin}	minimum cold utility requirement (kW)
Q_h	total hot utility used (kW)
Q_{hmin}	minimum hot utility requirement (kW)
Q_j	enthalpy of section j (kW) [Figure 2.5]
q_k	enthalpy of stream k (kW) [Figure 2.5]
Q_{max}	maximum heat load for a match (kW)

Q_S	the hot utility used in any interval k, (Q_{ik} $)_{i=S}$
Q_W	the cold utility used in any interval k (Q_{jk} $)_{j=W}$
R	heat capacity ratio
R_{ik}	the residual of hot stream i in interval k
RM	the set of restricted matches
s	number of separate components
S_{min}	quasi-minimum number of exchangers for achieving minimum area
S_{ukl}	utility consumption
T_0	the environmental temperature (290 K)
T_c	average cold stream temperature (K)
T_{cs}	cold-stream starting temperature (°C)
T_{ct}	cold-stream target temperature (°C)
T_h	average hot stream temperature (K)
T_{hs}	hot-stream starting temperature (°C)
T_{ht}	hot-stream target temperature (°C)
T_{pp}	pseudo-pinch temperature (°C)
T_s	starting temperature (°C)
T_t	target temperature (°C)
T_w	maximum temperature of cooling water (°C)
U	overall heat transfer coefficient (kW/m^2K)
U_k	operating cost of utility S_{uk} per year
U_{minMER}	Minimum number of units in a MER network
$U_{min_{sec}}$	minimum number of units in a section
U_{min}	minimum number of units
$\triangle Ex$	change in exergy flowrate (kW)
$\triangle H$	change in enthalpy flowrate (kW)
$\triangle S$	change in entropy flowrate (kW/K)
$\triangle t$	approach temperature (K)
$\triangle t_a$	actual LMTD of the exchanger in the network (K)
$\triangle T_{av}$	average temperature difference (K)
$\triangle t_{con}$	individual stream contribution (K)

Δt_{ec}	effective stream contribution (K)
Δt_{Emin}	exchanger approach temperature (K)
ΔT_{LM}	LMTD (K)
Δt_i	minimum approach temperature (contribution of stream i) (K)
Δt_{max}	maximum temperature difference on the composite curves [Figure 3.16]
Δt_{min}	minimum approach temperature (K)
Δt^M_{min}	match dependent minimum approach temperature (K)
Δt_{Nmin}	network approach temperature (K)
ΔT_S	the smallest actual temperature difference within the exchanger (K)
Δt_v	LMTD if the exchanger is vertical when placed against the composite curves
w	flow rate of a stream (kg/hr)

Greek Symbols

α	minimum additional utility requirement for a feasible constrained network (kW)
α	heat transferred across the pinch (kW)
α_i	heat transferred across the pinch by stream i (kW)
β	constant in equation (E.1)
β	area efficiency (see Figure 7.12)
δ	downtime (hrs/yr)
γ	constant
ϕ	maintenance charge
ψ	exergy efficiency
ξ	capital-recovery factor

Summary

This thesis discusses the problem of synthesizing optimal heat exchanger networks. It may be divided into two parts. Part I concentrates on the generation of cost optimal networks which exhibit maximum energy recovery (MER). A method has been presented for estimating the minimum number of shells required by the network, for a given value of minimum approach temperature, $\triangle t_{min}$. This value of $\triangle t_{min}$ is assumed to be constant for each heat exchanger unit present in the network. Assuming an exponential cost equation, a range in which the global optimum value of $\triangle t_{min}$ is likely to be found is predicted independently and *a priori* of the detailed design. A methodology based on the concept of "degree of criss-crossing" is also presented to achieve the predicted shell targets and the minimum network area target, resulting in cheaper capital cost designs. Finally the problem of designing MER networks, the data for which exhibits multiple pinch points is discussed.

As the capital cost of any network is dependent on the number of units, the problem of devising systematic methods to evolve network topologies featuring close to the minimum number of units has been investigated in part II. Normally to achieve this, energy has to be 'transferred' across the pinch point. As a consequence, the final design features two approach temperatures - exchanger minimum approach temperature, $\triangle t_{Emin}$ and network heat recovery approach temperature $\triangle t_{Nmin}$ (the pinch point $\triangle t_{min}$). The latter approach temperature establishes the total utility consumption of the network.

In Part II, two approaches are proposed to synthesize networks with the characteristics discussed above. In the first approach, the energy consumption of an initially synthesized MER design employing the standard pinch design method, is relaxed. A mixed integer non-linear programming model is proposed and a systematic method for energy relaxation based on 'best-first' search strategy is developed. Limitations inherent to this approach have been identified.

In the second approach, the concept of a "*pseudo-pinch point*" is proposed. Utilizing this concept, simple and elegant network designs can be generated by hand calculations even for complex industrial problems. It has the advantage of keeping the designer in the "driving seat" so that he can, with his expertise and knowledge about the process, create practical designs.

Finally, a systematic design procedure to handle designer imposed constraints is presented. To account for *match* constraints, heat has to be transferred across the unconstrained thermodynamic pinch point. However, the standard pinch design method fails to generate systematically solutions to such networks. Furthermore, the basic principles employed by the pinch design method are also invalid under the imposed *matching* constraints. The proposed new method is based on the idea of individual "stream heat cascading".

Plausible concepts worth further investigation are also reported. These include, extension of the pseudo-pinch concept to heat and power integration, integration of distillation columns and total plant integration. The pseudo-pinch point concept can also be modified to develop systematic procedures for retrofitting. The concept of a *dominant pinch point* for simplifying the design procedure when designer imposed constraints are involved is also presented. The idea of further extension of this concept to practical total plant integration is also covered.

In this thesis, design methodologies and philosophies are developed and discussed so that the insights gained during this study can be practically applied to the design of complex industrial problems. These insights are simple and reflect a fundamental understanding of the process synthesis problem. The concepts and the methods reported are ideal for the future development of a real time expert system for total plant integration.

Declaration

This thesis contains no material which has been accepted for the award of any other degree or diploma in any University and, to the best of the author's knowledge and belief, the thesis contains no material previously published or written by another person, except where due reference is made in the text or where common knowledge is assumed.

(Kirtan K. Trivedi)

Acknowledgements

My sincere thanks are due to Dr. J.R. Roach for his guidance in this research project. Valuable discussions and guidance offered by Dr. B.K. O'Neill is highly appreciated by the author. Special thanks to Dr. R.M. Wood, School of Chemical Engineering and Industrial Chemistry, the University of New South Wales, for his valuable comments in the developments of some of the procedures outlined in this thesis. Also, I feel indebted to the University of Adelaide for providing the financial resources, and to Professor J.B. Agnew, as the head of the department, for the encouragement to spend these years at the University of Adelaide. Thanks are also extended to the computing services of the university and especially, Mr. Johnathan Willmore for his assistance in the development of the necessary software required for this study. The generous help obtained from Ms. Kay Leverette and the Barr Smith Library staff for their assistance in obtaining the relevant literature is highly appreciated. Thanks are also due to Mr Kym Ide for proof reading this thesis.

I was fortunate to attend a master class conducted by Professor Bodo Linnhoff, UMIST, U.K., during the initial stage of this project. I am grateful to him for the discussions we had at this class which exposed me to the mysteries of 'pinch' technology and furthermore for inspiring me to keep things simple and to avoid 'black boxes' as far as possible.

More privately, I would like to thank my family members and friends who have continually given me the support and encouragement needed during the course of this study. Thanks is also extended to Richard Raszka, Trevor Brown, David Dunne, Andy Zwahlen, Bill Mitchell, postgraduate students, faculty, and workshop staff of the department and to all my friends in Kathleen Lumley College who have made my stay in Australia most enjoyable and memorable.

Finally, I want to close with a special acknowledgement: to Dr. Gopesh Srivastava, Department of Biochemistry, for his friendship, encouragement and inspiration when most needed.

(Kirtan K. Trivedi)

Divide each problem that you examine into as many parts as you can and as you need to solve them more easily.

Descartes,
OEuvers, vol. VI, p.18;
"Discours de la Methods"

This rule of Descartes is of little use as long as the art of dividing ... remains unexplained ... By dividing his problem into unsuitable parts, the inexperienced problem-solver may increase his difficulty.

Leibniz,
Philosophische Schriften,
edited by Gerhart, vol. IV, p.331 from
George Polya,
Mathematical Discovery

Chapter 1

Introduction

The major elements of most chemical plants can be represented as illustrated in Figure 1.1. In this plant the raw materials are converted into products. This conversion takes place in the "heart" of the plant, the *reactor.* The reaction products are separated from the unreacted raw materials (normally recycled), impurities (undesired products or by-products) and the desired pure products. This activity is perpetuated at the expense of energy either in the form of heat or power.

In a typical integrated plant, the raw materials are heated/cooled to the appropriate reaction temperature. Heat may be added/removed to carry out the reaction at the correct conditions of temperature and pressure. The product separation is achieved by heat addition (to a reboiler in a distillation column) and removal (from a condenser of the distillation column). The products may be heated/cooled to the correct temperature for storage and transportation. Thus, at all times heat is either added or removed to a variety of process streams by utilities or by heat exchange between process streams. In an integrated plant this is normally achieved with a *heat exchanger network* (HEN). A large fraction of the capital cost of many petrochemical

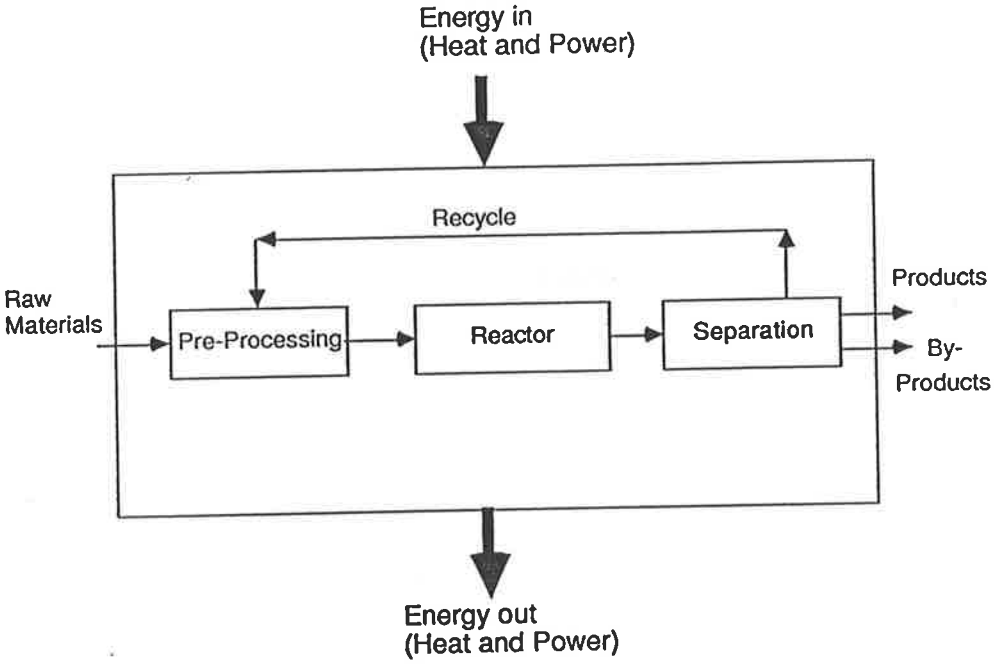

Figure 1.1: Representation of a typical chemical plant

plants is attributed to heat recovery networks.

The aim of a process designer is to synthesize a near cost optimal configuration. This indicates that a proper trade-off between the capital invested and the operating cost of the plant should be achieved. The capital cost mainly depends on the number of units utilized to satisfy the objectives. A substantial part of the operating cost usually depends upon the utilities consumed. To reduce these costs, the process designer should aim for an economic combination having a near theoretical minimum number of heat exchanger units and aim to recover the maximum possible heat with them. Futhermore, the designer should also investigate operability factors. An obvious way to recover heat is by exchanging it between hot process streams and cold process streams[1] in addition to the heating and cooling by utilities.

To satisfy the above objectives it is important to synthesize a good heat exchanger network. The problem is highly combinatorial in nature and a large number of alternatives exists. Westerberg [158] has noted, "one can enumerate 47 different structures for exchanging heat among two hot and two cold streams where one disallows the splitting of any of the steams, where no two streams may exchange heat between them more than one time, and where each match must involve heat transferring only from a hot stream to a cold stream ... if one has three cold and two hot streams the number of alternatives is 847." This combinatorial nature has also been noted by several other researchers. According to Ponton and Donaldson [124] for a problem involving N_{hot} hot streams and N_{cold} cold streams the number of different topologies possible are of the order of $(N_{hot} \times N_{cold})!$. Thus, for a typical complex industrial situation eg. a crude pre-heat train having fourteen hot streams and eleven cold streams, the magnitude of the number of topologies would be 154!, a very large number. Linnhoff [88] has reported similar results. He has proposed a formula which accounts for the utility matches neglected by Ponton and Donaldson. According to his calculation, for an eight stream problem having the same number of hot and cold streams, a total of 2.3×10^{87} different topologies are possible.

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[1] Hot streams are defined as the streams which are to be cooled and cold streams are defined as the streams which are to be heated.

As noted earlier, the capital and operating cost of the network contributes a considerable fraction to the profitable and economic operation of a plant. Furthermore, due to the existence of a large number of alternatives it would appear to be highly rewarding to be able to synthesize quickly and systematically the best possible alternatives.

Again, operability and flexibility characteristics of a heat exchanger network influence the flexibility of any chemical plant [44]. Different heat recovery networks have vastly different operating characteristics. Hence, one of the aims of this study is to develop systematic methods to identify a number of different alternative designs having comparable near optimum overall costs.

Considerable developments have been made during the last decade due mainly to the efforts of Linnhoff and his co-workers. A breakthrough has been made and a new 'Pinch Technology' has evolved. It has been successfully applied to process integration [90] which encompasses overall plant integration and includes heat exchanger networks, heat and power networks, and thermal integration of distillation columns etc. While 'Pinch Technology' has proved to be effective, it is not complete and there are certain fundamental questions which have yet to be investigated. Unjustified but plausible heuristics have been used. The main thrust of this study is to justify these heuristics wherever possible or to replace them by developing formal systematic methods. Of the many questions raised in the literature survey (see chapter 2), this thesis attempts to answer the following:

1. How do we target for the minimum number of shells ?
2. How do we predict the optimum value of Δt_{min} ?
3. How to design for minimum capital cost for a given level of maximum energy recovery ?
4. How to handle multiple pinch situations ?
5. How to reduce systematically the number of units in a given initial design with a minimum energy penalty ?

6. How to identify systematically all the feasible designs for a given energy recovery and minimum exchanger approach temperature ?
7. How to implement systematically designer imposed constraints on stream matching in the synthesis of HEN ?

Chapter 2

Literature Survey

2.1 Introduction

The problem of heat exchanger network (HEN) synthesis has been studied by a number of researchers. An excellent review of the developments that took place prior to 1981 is given by Nishida et al. [109], Stephanopoulos [140] and Westerberg [158]. A summary of the developments that took place before 1981, followed by a detailed review of developments that took place after that year, are presented in this chapter. A detailed discussion of the published papers and the various approaches used for solving the HEN synthesis problem is also presented. Finally, problems requiring investigation are identified and those which will be pursued in this study are outlined, and the approach employed in the present study is introduced.

2.2 Problem Formulation

Masso and Rudd [105] in 1969 formulated the heat exchanger network synthesis problem as follows:

> "*Task Constraints:* There is a total of N_{stream} liquid process streams N_{cold} of which are to be heated, while the remaining $N_{hot} = N_{cold} - N_{stream}$ streams are to be cooled. Associated with the ith stream are its flow rate, w_i, input temperature T_s^i, output temperature, T_t^i, and heat capacity, c_p^i, all in consistent units. The available auxiliary heat transfer media are saturated steam and cooling water. The steam is avaliable at any flow rate at a pressure p_s, and is allowed to give up only its latent heat l_s. Cooling water is also avaliable at any flow rate at a temperature T_s^w, and is allowed to undergo changes up to a maximum temperature T_w.
>
> *Unsynthesized System:* The unsynthesized system has input information consisting of a stream descriptions given above, and additional data representing further constraints to be listed below.
>
> *Existing Technology:* The equipment includes heat exchangers of shell-and-tube type operating as counter-current, single-pass units. For the fluids and conditions prevailing, average overall heat transfer coefficients U_{HE}, U_E, and U_C are achievable for heat exchange between any two process streams, steam heating, and water cooling, respectively. For heat exchange, heating, and cooling, the minimum allowable approach temperature differences are $\triangle t_{min_{HE}}, \triangle t_{min_H}$, and $\triangle t_{min_C}$, respectively. The equipment undergoes maintenance checks and repairs resulting in δ hours of downtime per year.
>
> *Economics:* The economics of the system, or any part of it, are represented by yearly costs and are determined by using the information that follows. Heat exchanger cost as a function of its area is given by a correlation of the form $C_u = a\,A_u^b$ where a and b are constants. Cooling

> water costs C_{water} \$/kg and steam costs C_{steam} \$/kg. Operating and other costs are neglected. Total costs amortizing linearly over a period of M years.
>
> *Synthesis Objective:* The objective is to structure a system capable of performing the prescribed tasks at minimum yearly costs."

This formulation was adopted in the subsequent studies reported on HEN synthesis. For most practical situations it is an overly simplified formulation and its limitations will be discussed in chapter 5. However, the specification closely represents the information typically avaliable to a designer from a process flowsheet which has not been 'integrated'.

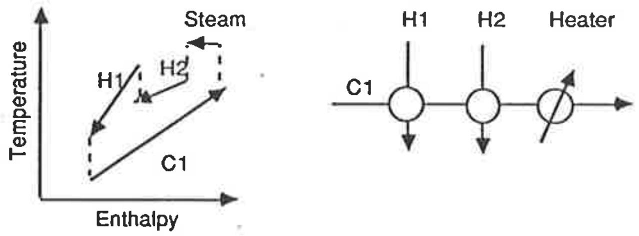
Various representations exists for the HEN problem. These are detailed in Figure 2.1 [109]. In this thesis the last representation, Figure 2.1d, the temperature interval or the *grid diagram* proposed by Linnhoff and Flower [96] will be used for illustrating the networks developed. The hot streams (being cooled) run from left to right and the cold streams (being heated) run from right to left. Stream matches are represented by circles on each of the streams connected by a vertical line.

An important modification of the temperature - enthalpy diagram (Figure 2.1a) [159] was proposed by Umeda et al. [154] and will be discussed in the next section.

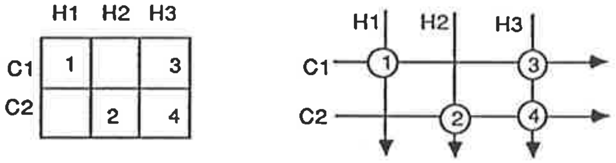
2.3 Synthesis Algorithm

There are three major steps reported in literature for synthesizing networks.

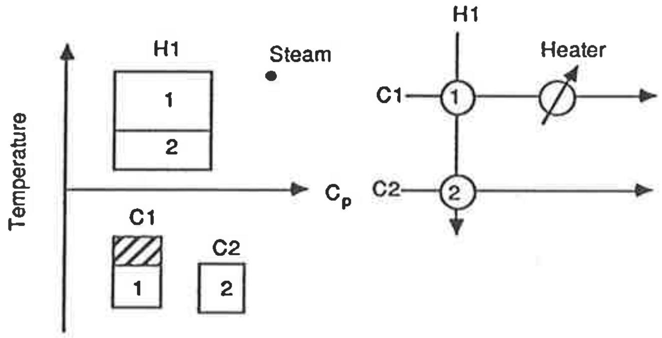
1. Target setting (establishing lower bounds on the search space).
2. Design/synthesis of an initial network.
3. Evolution of the initial designed network to produce a final practical design.



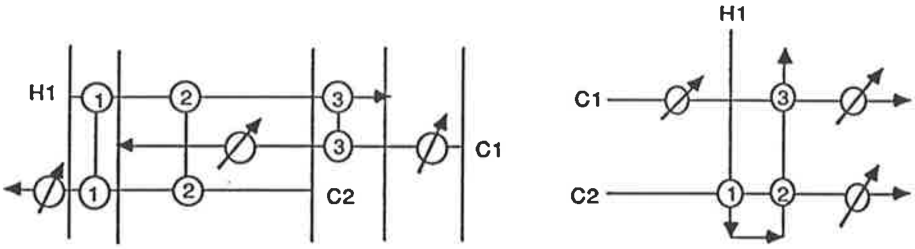
(a) Temperature-enthalpy diagram



(b) Matrix representation



(c) Heat content diagram



(d) Temperature Interval diagram

Figure 2.1: Representation of heat exchanger networks (a) - (d) [109]

This philosophy has been accepted by practising engineers as one of the best strategies for solving the HEN synthesis problem. Targets provide the stimulus to generate better designs and establish confidence in the evolved network.

2.4 Targets

Targets are established prior to design. Presently, three targets are easily established. For a given stream system these are

1. The maximum energy that is recoverable (minimum utility consumption) for a given value of $\triangle t_{min}$ (Energy targets).
2. Minimum network heat exchanger area (Area target).
3. Minimum number of heat exchanger units (Unit target).

These are practical targets. The first target (minimum energy consumption) can always be achieved, albeit with some additional capital cost. The minimum network area can be approached. However, the last of the three viz. minimum number of units is problem dependent and can normally be achieved at the expense of employing utilities in excess of the theoretical minimum required, or by using excessive area.

2.4.1 Energy Targets

Three bounds on the energy targets can be predicted. A bound [109] can be derived from the First Law of thermodynamics based on the difference between the hot and cold utilities used. According to this law,

$$Q_h - Q_c = \text{constant}$$

where, Q_h is the total hot utility used and Q_c is the total cold utility used.

Another lower bound that accounts for the portions of hot streams colder than any existing cold process streams (or cold streams hotter than any existing hot process streams) was predicted by Rathore and Powers [127], Nishida et al. [112], and Grossmann and Sargent [46]. However, exact targets can be established by the methods of Umeda et al. [154] and Linnhoff and Flower [96]. Umeda et al. modified the temperature-enthalpy diagram illustrated in Figure 2.1a. Its construction is illustrated in Figure 2.2. A composite curve can be obtained for both the hot and cold process streams. These composite curves can be shifted in the horizontal direction till they are vertically $\triangle t_{min}$ apart at some point on the ordinate. This modification helped in targeting prior to design, the minimum energy requirements and identifying the 'bottleneck' in a process design which precludes further heat integration (Figure 2.3). Using the composite curves for a given value of $\triangle t_{min}$, the utility quantities predicted are the absolute minimum required to solve the heat recovery problem. The minimum cold and hot utility requirements are Q_{cmin} and Q_{hmin} respectively. Another important feature of this diagram is the *pinch point* which is the 'bottleneck' for process integration. It is the point where the composite curves are $\triangle t_{min}$ apart. This point was also identified by Linnhoff and Flower [96] using the *problem table algorithm.* The identification of the pinch point had a great impact on the fundamental understanding of the HEN synthesis problem and has led to the development of effective and efficient design procedures. These sophisticated techniques were first proposed in a crude form by Hohmann [56]. A 'cumulative heat deficit' method was also proposed by Raghavan [126] for setting energy targets. These methods for predicting the targets are best suited for hand or graphical calculations and are in essence a simple heat balance.

Cerda et al. [20] and Papoulias and Grossmann [117] used mathematical programming methods to predict this target. Cerda et al. formulated the problem as a "network flow" model in linear programming and extended the method to include stream matching constraints and match dependent $\triangle t_{min}$ values. Townsend and Linnhoff [152] have modified the problem table analysis to include the latter situation. Papoulias and Grossmann have formulated the targeting problem as a "trans-shipment" model. The analogy proposed by them is that "heat can be regarded as a com-

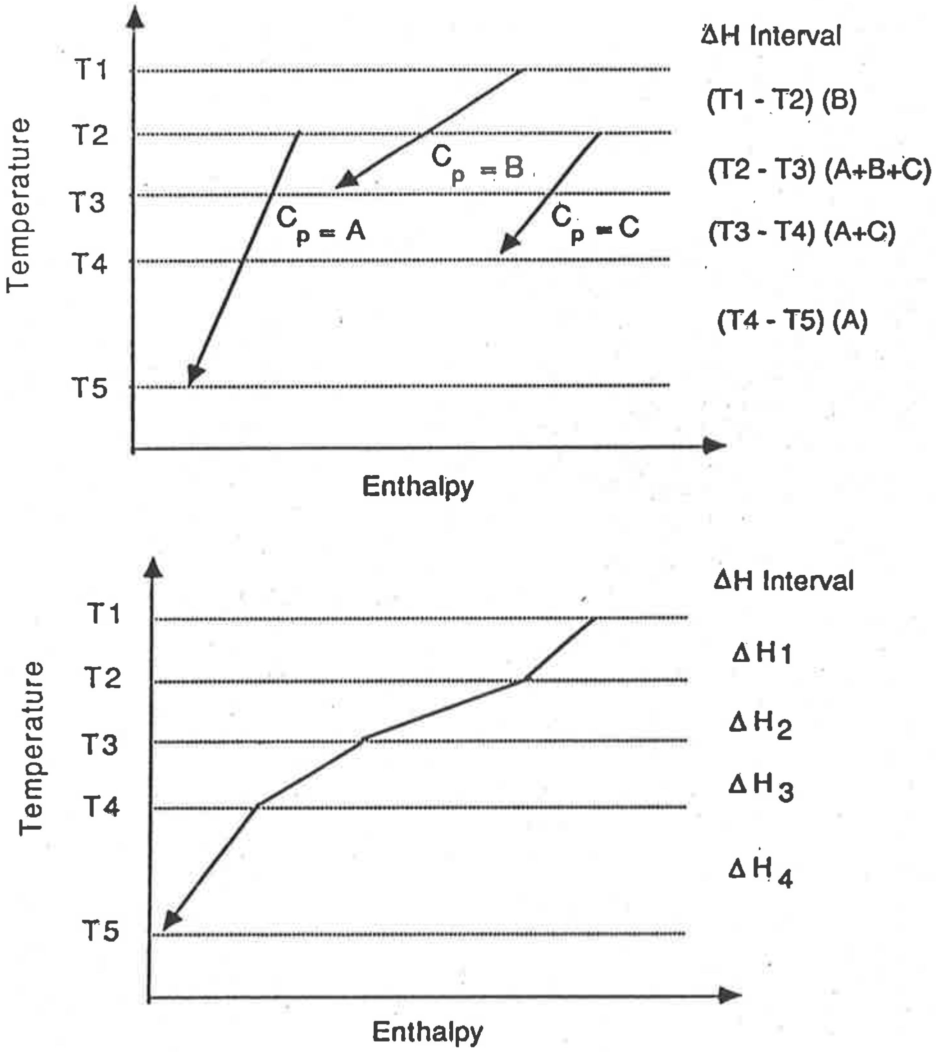


Figure 2.2: Construction of the composite curves [100]

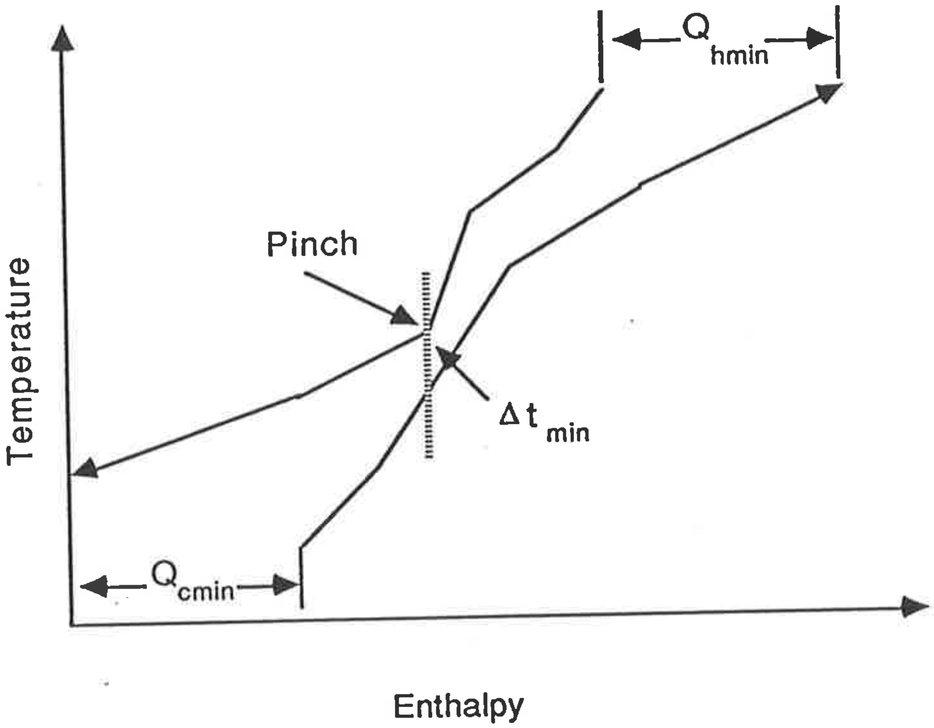


Figure 2.3: Energy targets and the “pinch” with the composite curves [100]

modity that is shipped from the hot streams to cold streams through temperature intervals that account for thermodynamic constraints in the transfer of heat." Papoulias and Grossmann have extended their formulation to include the constrained stream matching case. It should be noted that if $\triangle t_{min}$ is the same for all matches then one can easily demonstrate that the problem table analysis of Linnhoff and Flower is a sub-set of the above two models. Futhermore, an algorithm similar to the problem table analysis does not exist for constrained stream matching cases.

2.4.2 Problem Partitioning for Predicting the Energy Targets

All the above analytical methods require that the problem data be partitioned into temperature intervals. For the feasibility analysis, Hohmann divides the stream system into temperature ranges. These temperature ranges are defined by the temperature constraints for all the source and sink streams. To obtain a set of temperature intervals for the analysis the convention has been adopted that the minimum approach temperature $\triangle t_{min}$ is added to all the sink stream temperature points. This ensures that the $\triangle t_{min}$ constraint is never violated [56]. A new temperature interval is generated each time a stream (source or sink) is encountered as the stream starting temperature list is scanned downwards through the temperature range. Similarly, a new range is also started whenever the terminal temperature of a stream is reached. The same temperature ranges are used for the problem table analysis. The temperature interval generation is illustrated in Figure 2.4. This partitioning scheme was employed by Linnhoff and Flower [96] in the problem table analysis. Grimes [43] modified this interval creation procedure. He notes that if all the streams are represented as a single straight line on the temperature - enthalpy diagram (assuming a constant C_p) then only the stream inlet temperatures need be considered to solve the minimum utility problem. These rules for generating the temperature intervals were subsequently generalized by Cerda et al. [20] since one of the aims of energy targeting is to locate the pinch point. They proposed

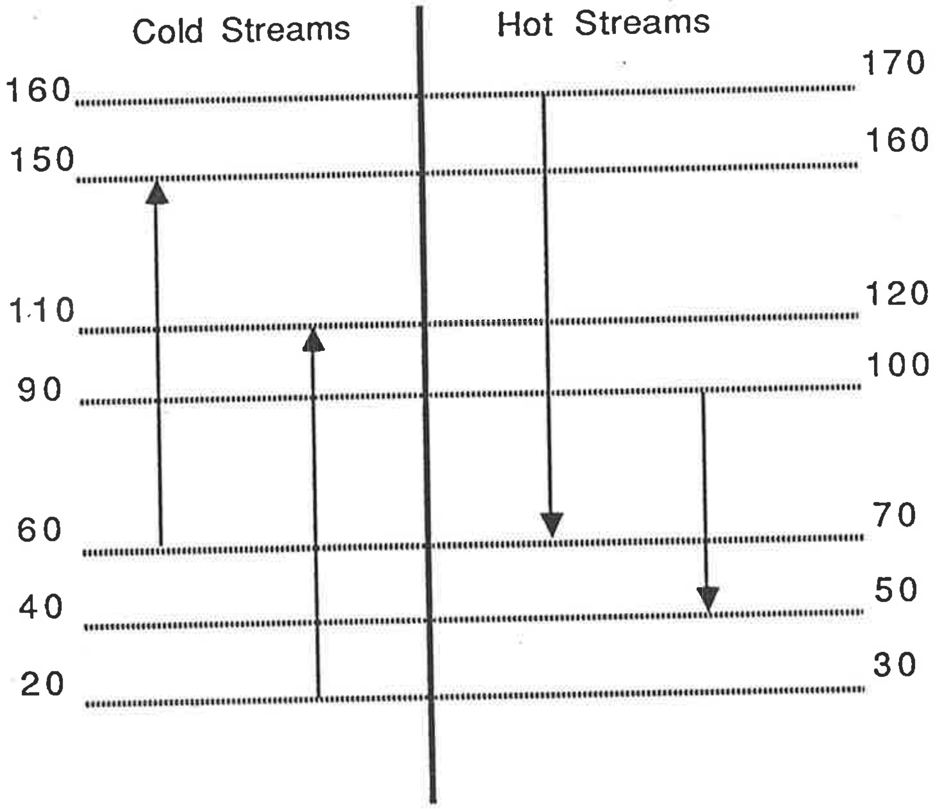


Figure 2.4: Generation of temperature intervals assuming $\Delta t_{min} = 10$ K

1. if a pinch point exists, it occurs at the 'corner points' (kinks)[1] for either the hot or cold composite curves;
2. not all corner points can be pinch points.

They have suggested simple rules to locate the corner points and that the stream system need only be divided at these corner points. Further, they noted that no temperature need be considered if it is out of range i.e. if it is along the merged stream and is more than $\triangle t_{min}$ above or below any of the temperatures spanned by others. These rules help in reducing the number of temperature intervals obtained by Hohmann's procedure by 50%. It may be concluded that for methods using only a global value of $\triangle t_{min}$ the method of Cerda et al. is the best.

A simple modification is recommended by Cerda et al. [20] to handle match dependent $\triangle t_{min}$ values. However, the number of partitions used increases enormously by implementing this modification. To account for match dependent $\triangle t_{min}$, Townsend and Linnhoff [152] have suggested the concept of $\triangle t$ 'contribution'. In this method the hot stream temperatures are reduced by their corresponding $\triangle t_{min}$ contribution and the cold stream temperatures are increased by their respective contribution. Employing this approach the modification suggested by Cerda et al. for generating the temperature intervals with a global $\triangle t_{min}$ cannot be used as their rules are no longer applicable. Townsend and Linnhoff have suggested that the original temperature intervals suggested by Hohmann be employed for the problem table analysis. For the case of a global $\triangle t_{min}$, they have recommended that $\triangle t_{min}/2$ be added to all the cold stream starting and target temperatures and the same quantity should be subtracted from the hot stream terminal temperatures. This is because the individual contributions simply become $\triangle t_{min}/2$. The actual stream data is now modified and all the temperatures can be represented on a single modified temperature scale. A problem table analysis on these modified temperature will give the same energy targets.

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[1] Corner points are where the composite curves change slope due to a change in the (C_p) values i.e. where streams enter and leave the composite line or phase change takes place.

2.4.3 Area Target

The concept of an area target was introduced independently by Hohmann [56] and Nishida et al. [110]. Both assumed an equal heat transfer coefficient for all the streams and that each differential element of heat for all the streams is exchanged in a manner similar to that for two streams in an ideal counter-current exchanger. This type of heat transfer is referred as "vertical heat transfer" [151]. The area target can be easily obtained from the composite curves by dividing it at the 'kink' points and substituting the value of the relevant variables into the equation 2.1

$$A_{min} = \frac{1}{U} \sum_j \left(\frac{Q_j}{\Delta T_{LM_j}} \right) \tag{2.1}$$

where the subscript j refers to linear counter-current section of the composite curve as indicated in Figure 2.5.

The target value obtained by the above equation is only very approximate for practical purposes because of the assumption of a constant overall heat transfer coefficient for all the streams. Townsend and Linnhoff [151] modified the above target to include individual film heat transfer coefficients. They have suggested the following formula (refer to Figure 2.5):

$$A_{min} = \sum_j \frac{1}{\Delta T_{LM_j}} \left(\sum_k \frac{|q_k|}{h_k} \right)_j \tag{2.2}$$

They have claimed that practical designs can be produced which have a total area within +10% to +15% of this target. However, Saboo et al. [130] have noted that this formula can overestimate the target area when the stream film heat transfer coefficients are significantly different. To improve this target they have proposed the use of a simple transportation model in linear programming (LP).

In the above methods for area targeting Townsend and Linnhoff, and Saboo et al. have assumed that the composite curves represent a single 'super' hot and 'super' cold stream exchanging heat in a single 'super' exchanger. Practical networks consist

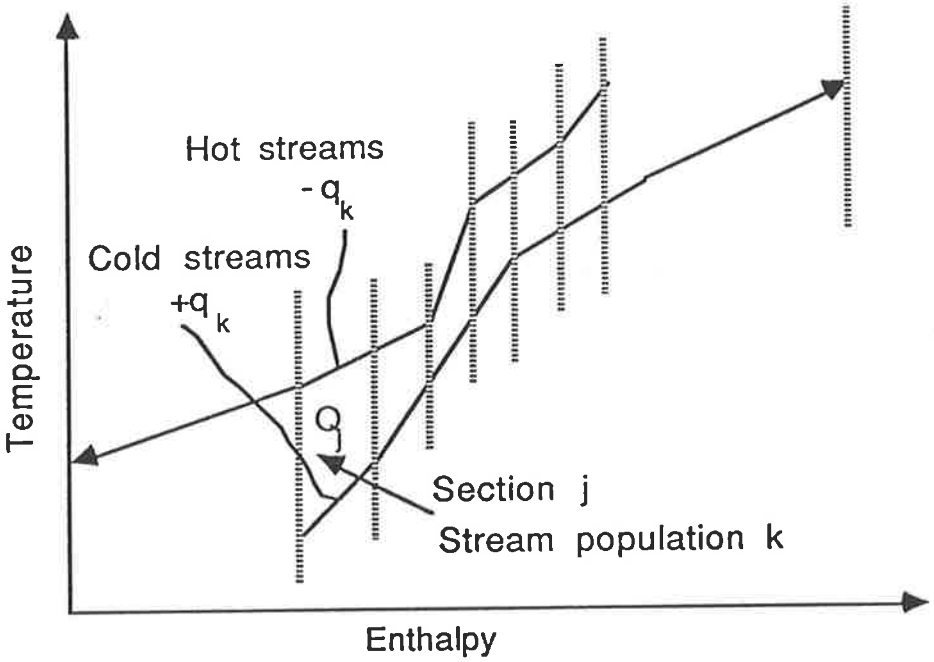

Figure 2.5: Division of the composite curves for obtaining an area target [151]

of individual units and the formula for area calculations for each unit should contain a temperature difference correction factor. Hence, to predict a precise area target, an effective logarithmic mean temperature difference (LMTD) correction factor, F_t should be included in the above equation. Another limitation of the above formula is that it assumes a single global $\triangle t_{min}$ for all the matches. An area target which features individual $\triangle t_{min}$ on each exchanger is still to be developed. Furthermore, as will be noted later, the final design often has an energy consumption greater than the minimum requirement which results in higher overall LMTD values and hence tends to reduce the required area. Therefore, although the above minimum area target is effective as a first approximate, a precise area target for practical networks is yet to be developed.

2.4.4 Minimum Number of Units

The concept of minimum number of units was first proposed by Hohmann (1971) [56]. He defined the "quasi-minimum" number of units for a stream system as

$$U_{min} = N_{stream} - 1 \tag{2.3}$$

where, U_{min} is the minimum number of units, N_{stream} is the total number of streams including hot and cold utilities. He also noted that a network may have more than quasi-minimum number of units if "heat load loops" exist. Later, Boland and Linnhoff [16] proposed a more generalized equation based on Euler's theorem from graph theory.

$$\begin{aligned} \text{Minimum number of units} \;&=\; \text{Total number of streams} \\ &+\; \text{Independent heat load loops} \\ &-\; \text{Number of separate components} \end{aligned} \tag{2.4}$$

$$U_{min} = N_{stream} + L - s \tag{2.5}$$

The term 'L' in equation 2.5 represents the total number of heat load loops present in the network. A loop is a closed path through the network, and its effect is to increase the total number of units. For a network to have minimum number of units, the total number of loops must be zero. Practical systems are usually analysed as independent problems with $s = 1$, that is "separate components" is treated as a distinct subnetwork. Substituting 0 for 'L' and 1 for 's' in the equation 2.5, equation 2.3 is obtained. This equation is a good predesign target. A network satisfying this target often is the optimum design because it is likely to approach minimum capital cost [91].

Similar targets (based on matches and not on units[2]) using mathematical programming techniques have been reported by Papoulias and Grossmann [117] and Saboo et al. [130]. Both have used mixed-integer linear programming (MILP) models to predict the minimum number of matches required and have employed the transshipment model. Papoulias and Grossmann divide the problem at the pinch points and also implement the constraint that the network should feature maximum energy recovery. Saboo et al. do not divide the problem at the pinch point. Their formulation increases the size of the MILP but provides the flexibility (gained from incremental utility inputs) crucial for solving practical problems. Thus, it allows the designer to specify more than the minimum amount of heating and cooling with consequently fewer loops which in turn results in a lower and better 'number of matches' target. However, neither of these models can be used to predict the minimum number of units for an *a priori* specified level of energy recovery. This problem was originally identified by Linnhoff in his thesis [88]: "There is clearly a challenge for future work in identifying an algorithm which based on stream data, will predict the smallest possible number of units."

The above discussion has reviewed three important targets. However, there are two more important targets for a network solution which have not been considered in the literature. They are

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[2] Matches and units are separate entities. The number of matches will be less than or equal to the number of heat exchanger units.

4. Shell target.

5. Optimum value of $\triangle t_{min}$.

2.4.5 Shell Target

Industrial heat exchanger units are made up of multi-pass shell-and-tube units. The number of shells required by the network plays a significant part in the cost of the final design. When this project was started the concept of shell targeting did not exist in the literature. It is an important aspect of HEN analysis and has been completely ignored to date chiefly because a majority of the researchers have used Masso and Rudd's [105] model which assumes that each unit is made up of a single shell. In this thesis a method will be proposed to obtain this target.

2.4.6 Optimum Value of $\triangle t_{min}$

The objective of the designer is to optimize the final network design. $\triangle t_{min}$ is an important parameter in the design of HEN. As this parameter fixes the area and the utility requirements, which are the prime variables for optimizing the total cost of the network, there is a large incentive to find its correct optimum value *a priori* to design. Doing so, will reduce the post-design optimization process as the initial network generated is likely to be quite close to the final global optimum.

Assuming a constant overall heat transfer coefficient for all the streams, Hohmann [56] proposed a method to determine the optimum value of $\triangle t_{min}$. Later Ahmad and Linnhoff [3] have removed the above assumption by employing the area targeting formula of Townsend and Linnhoff [151]. They have assumed that each exchanger unit is made up of a single shell and certain unspecified simplifying assumptions are made in order to combine the area and the units target in terms of actual costs.

Linnhoff and Hindmarsh [91] search for the optimal pinch approach temperature using the pinch design method by costing several partial designs on the basis of changes in the pinch match costs. Floudas et al. [29] applied the "golden section" search method in an outer loop of their proposed synthesis procedure and used total design costs.

Li and Motard [82] have made unrealistic assumptions in deriving a formula for predicting the optimum value of $\triangle t_{min}$. They substitute straight lines for the hot and cold composite curves above and below the pinch point. This is clearly an over simplification. Futhermore, all these methods have assumed that each unit is a single shell exchanger. So, the values predicted by these methods could be fallible for the generation of globally-optimal but practical networks. It is proposed to include an investigation of the problem of finding the correct optimum value of $\triangle t_{min}$ in this thesis.

2.5 Design

The design procedure for network generation has followed the strategy outlined by Masso and Rudd [105]. They have shown that the principle of problem decomposition holds promise as a practical means of system synthesis. They had envisaged that "... synthesis may be gainfully approached by development of techniques for progressively breaking large problems into smaller, more manageable, subproblems ..." The solutions to the subproblems are then combined and refined to a practical but near optimal solution by using evolutionary rules. Almost all the methods proposed to date have followed this approach. The HEN synthesis problem is partitioned into temperature intervals (each of which generates a different subproblem) by the methods outlined in one of the previous sections. Other models for sub-problem generation have been proposed, based on completed and uncompleted design sections [81,105]. Modifications of these basic partitioned strategies depended in each case upon the individual methods selected for evolving the designs.

Selection of matches takes place in parallel or a sequential manner. Nishida et al. [109] have classified the matching algorithms as 'sequential match decision algorithms' and 'simultaneous match design algorithms'. Some of the algorithms developed after this review was published featured a simultaneous and sequential strategy for deciding stream matches [91].

2.5.1 Sequential Match Decision Algorithms

This class of algorithms [109] is based on various search mechanisms by developing a search tree. Heuristic rules are used for further generating the nodes to be investigated e.g. branch and bound or depth first search strategies. Table 2.1 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 various algorithms [109].

Total and partial enumeration techniques in combination with what turned out to be a fallible "look ahead" procedure was proposed by Pho and Lapidus [121]. Kafarov et al. [69,68] have also reported a similar method. This method is not suitable for synthesizing complex networks as the search tree becomes excessively large. Branch and bound strategy has also been recommended by others [81]. However, this strategy used the erroneous heuristics HR-1 to HR-4 to select matches, and a lower bound based on one of the following for guiding the search:

1. annualized cost
2. utilities
3. number of units
4. a combination of the above.

A case study employing depth first search strategy is reported by Jezoeski and Hahna [65] which used bounds on utilities and the number of units for generating the search tree. It generated 111,382 nodes for finding the solution to a 20 stream problem and the computing time required was large.

Dynamic programming methods have been also been investigated by Westbrook

Table 2.1: Sequential match options [109]

Search Strategy Employed

SS-1: Total Enumeration.
SS-2: Branch and Bound.
SS-3: Heuristic.
SS-4: Others.

Heuristics Used (If SS-3 Employed)

HR-1: Select hot stream with highest inlet temperature and cold
HR-2: Select hot stream with coldest target temperature and cold stream with coldest inlet temperature.
HR-3: Select match giving least value of Δt_{av}.
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 of 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.

[157] and Hama [49]. Hama uses the corrected temperature difference derived by Nishimura and Yagi [113] using Pontryagin's maximum principle as the match selection criterion :

$$CTD_{ij} = \frac{T_{h_i} - T_{c_j}}{\sqrt{c/U_{ij}}} \tag{2.6}$$

The sequential approach for deciding the stream matches normally requires sophisticated computer programs and a satisfactory explanation as to why the evolved networks are allegedly optimal cannot be obtained. Moreover, the designer has no control over the synthesis and evolution of the network.

2.5.2 Simultaneous Match Decision Algorithms

Matching decisions for this type of algorithms fall into two categories. The first is based on mathematical programming procedures. The second is the thermodynamic combinatorial (TC) algorithm of Flower and Linnhoff [33].

Mathematical programming models solve some form of a linear program. The assignment algorithm of LP was proposed by three authors [19,75,77]. It only gives the possible matches. The designer is left to actually assign the heat loads and place units into an appropriate configuration. This type of problem has a very large solution space and a specification of a system for precise minimum utility consumption cannot be systematically achieved [22].

The mixed-integer linear programming (MILP) approach has been reported by Kelahan and Gladdy [70], Cerda and Westerberg [22], Papoulias and Grossmann [117] and Saboo et al. [130]. While Kelahan and Gladdy have employed the adaptive random search procedure, Cerda and Westerberg relax the MILP formulation to form a transportation model and solve it using the "reverse stepping stone algorithm". Papoulias and Grossmann proposed the trans-shipment model which was subsequently modified by Saboo et al. The solution to the model was obtained using the computer program LINDO [134]. This latter approach has proved to be quiet effective.

2.5.3 Simultaneous and Sequential Match Decision Algorithms

Linnhoff and Hindmarsh [91] used this approach in the development of the *pinch design method.* The problem is divided first into two independent subproblems at the pinch point with the result that heat is not transferred across this point. This division was first suggested by Grimes [43]. Each subnetwork is then designed independently. Explicit rules (C_p rule) are avaliable for simultaneous stream matching at the pinch point [91]. This method also indicates when stream splitting is required at the pinch point. The remaining matches i.e. the non-pinch matches are then placed sequentially. No explicit rules have been proposed for these decisions. The complete network is obtained by merging the two subnetworks. The initial design thus obtained is then evolved to a final near optimal design solution. This procedure is the most popular design method and has proved to be successful in the development of the so called "Pinch Technology" for process integration in which employing the pinch principle i.e. heat should not be transferred across the pinch, systematic methods have been developed for generating effective designs leading to substantial energy savings [90]. Detailed discussion of this method is presented at appropriate places in the thesis.

2.6 Network Evolution

A number of methods have been presented in the literature to aid the simplification of an initially generated network. The simplification process normally reduces the total number of units in the network and where possible removes stream splits.

Shah and Westerberg [135] suggested three rules which should be repeatedly applied to make modifications on the initial network and the subsequently evolved designs. The algorithm was to make a small change, if it led to an improvement, move to the improved network and repeat [109]. Nishida et al. [112] also reported three evolutionary rules which must be applied in numerical order to a complex network having minimum area obtained using their procedure [110]. As the initial network has minimum area, it normally has a large number of small units and stream splits.

In the evolutionary development (ED) procedure proposed by Linnhoff and Flower [96] a set of ten rules based on the concept of "freedom", F:

$$F = CP_L(\Delta T_S - \Delta t_{min}) \tag{2.7}$$

is enunciated. (CP_L is larger C_p of the two streams associated with a match and ΔT_S is the smallest actual temperature difference within the exchanger.) These rules are used to derive a final network from the initial network generated by the temperature interval (TI) method [96].

Strategies to break loops in networks generated by the TI method have also been developed by Su and Motard [142]. Their method is a more generalized scheme that subsumes the evolutionary rules proposed be Nishida et al. [112]. Colbert [25] employs Su's method in a synthesis method similar to TI and is discussed in detail later.

Grimes et al. [42] suggested seeding the network with dummy exchangers to investigate and to evolve alternate designs. Wood et al. [160] have employed stream splitting and by-passing to achieve both minimum number of units and maximum energy recovery simultaneously. In the pinch design method, Linnhoff and Hindmarsh [91] remove a unit by increasing the total energy consumption of the initial network.

Lastly, Floudas et al. [29] generate a superstructure derived from the matches obtained on solving the MILP trans-shipment model of Papoulias and Grossmann [117]. They solve a non-linear program to derive the final network design. Saboo et al. [130] use additional constraints coupled with the ED rules to evolve the network obtained from the solution of the MILP model.

All the design methods discussed above can be broadly classified into two categories:

1. Mathematical programming methods
2. Systematic evolutionary methods

The synthesis techniques based on mathematical programming aim to produce a network of minimum cost satisfying a specific set of constraints. However, so far these methods seem to have problems producing 'practical networks' for industrial problems. The systematic evolutionary methods develop an initial network which is modified towards a final optimal network. In the last five years, systematic evolutionary methods seem to have been accepted as the best available methods for generating networks. They are fairly simple to comprehend and implement.

Methods reported until now have assumed that a good network has a single global Δt_{min} and that it features maximum energy recovery. However, Colbert [25] and his group (SimSci) have taken a different approach. They assume that an optimal industrial network will feature an energy consumption greater than the minimum requirement corresponding to the minimum exchanger approach temperature. This approach has been totally ignored in the general literature and will be discussed later in this thesis (see chapter 4).

A detailed discussion of some of the above papers is presented in the thesis when warranted.

2.7 Total Plant Integration

The pinch design method and the pinch principle have led to the development of strategies for total process plant integration. Systematic procedures have been identified for process modification [90], heat and power integration [26,116,152], heat integration of distillation columns [7,8,55,85]. These ideas have been further extended to evaporators, flash systems, and chemical reactors [72]. Insights into development of procedures for retrofitting existing plants are presented by Tjoe and Linnhoff [149] and Jones et al. [66]. A lot of work has been reported in the area of designing flexible and operable HEN. As the scope of this thesis is limited to the synthesis of steady state HEN the above areas have not been discussed in detail but plausible extensions of the methods developed during this study are detailed in Chapter 7.

2.8 Avenues for Further Investigation

This review of the literature indicates that synthesis of HEN's is becoming a mature field of investigation. However, many questions are still unresolved. In the IChemE guide on 'Process Integration for the Efficient Use of Energy', Linnhoff et al. [100] have identified the following list of questions:

1. *How do we properly exploit process flexibilities (such as reaction temperatures, distillation column pressure and reflux ratio, side stream take-off points, etc) ?*
2. *How do we design for good operability ?*
3. *How do we allow systematically in our designs for constraints such as forbidden and imposed matches ?*
4. *How can we target more precisely for capital cost than by simply predicting the "number of units" ? How can we take into account individual stream film heat transfer coefficients, material of construction, engine size and efficiency, etc ?*
5. *How can we deal properly with the problem of trade-offs in complex design ? How can we guess the best value for* $\triangle t_{min}$ *? How can we trade-off the number of units against stream splits against total surface area against energy ?*
6. *How can we extend the techniques so as to give us good systematic procedures away from the pinch point ?*
7. *How do we modify the techniques so that they become explicitly applicable to "retrofit" designs ?*

These questions are solely based on the study of the pinch design method and its extensions. In addition to the above questions, the review presented in this chapter has raised the following new questions:

1. How can we systematically evolve designs from a given initial design without using unjustified heuristics ?
2. In actual networks, units are made up of multi-pass shell-and-tube heat exchangers. How can we target for the minimum number of shells and achieve it in actual practice ?
3. Since much of the significance of the pinch concept is lost if energy consumption is relaxed (ie. one is allowed to use more energy than the minimum) [15] and since the pinch design method has overly restrictive matching rules, do different topologies, having competitive capital-energy costs but possibly superior operability characteristics, remain undiscovered ? It is very important to assess these different potential topologies as each topology may have vastly different operating characteristics [44].

The goal of this study is to investigate the questions 3,4,5,6 proposed by Linnhoff et al. [100], in addition to the latter three questions put forward by the author.

2.9 Overview of the Thesis

In the author's opinion, the design philosophy elucidated by Linnhoff and co-workers is the best of the current methodologies because it provides detailed insights. Hence, care has been taken when developing new procedures to ensure that they provide fundamental insights and do not rely heavily on 'black box' computing. Computers should be only employed as a computational tool (including symbolic computation). The methods developed are flexible, practical, and the designer remains in complete control over the development of the design. Justified targets have been set ahead of design to aid in the identification of an optimal search space.

To aid the reader in following(understanding) the concepts proposed in this dissertation the following outline of the thesis is presented.

Chapter 3 considers the shell targeting problem and proposes a design method for identifying an optimum value of $\triangle t_{min}$ prior to design with some simplifying assumptions. Currently an ambiguity exists in the established *pinch design method* when the problem data features multiple pinch points. A method is suggested to overcome this ambiguity. Primarily, this chapter emphasizes the development of optimal designs featuring maximum energy recovery.

Chapter 4 discusses the problem of energy relaxation of an initial MER design. A detailed study of the existing heuristics for evolution of the the initial design is given. Formal justification or counter examples are presented to invalidate the existing energy relaxation heuristics proposed in literature. A systematic method based on the 'best-first' search technique [129] of Artificial Intelligence is proposed to overcome the fallible existing heuristics.

Chapter 5 presents the results of an investigation into the problem of synthesizing networks which feature energy consumption greater than the minimum required corresponding to a practical global $\triangle t_{min}$. A new design method is developed based on the concept of a *pseudo-pinch.* The proposed design method retains the advantages of the existing pinch design method but has considerable advantages. All possible topologies for a given energy consumption together with a given value of minimum exchanger approach temperature are quickly identified.

Chapter 6 details the systematic implementation of designer imposed matching constraints. A new design method based on the matching rules identified in chapter 5 has been developed.

Finally, in **Chapter 7** conclusions and recommendations for future work have been reported. Plausible concepts for a number of problems warranting further investigation and not discussed in the literature review are presented. These are particularly important in the development of a strategy for total process integration.

Chapter 3

Synthesis of Optimal Maximum Energy Recovery Heat Exchanger Networks

3.1 Introduction

A problem in the design of HEN's is the prediction of the total minimum number of shells[1] required in a network. In the established network-synthesis procedures [100], each exchanger unit is assumed (without verification) to be a single shell. However, the estimated capital cost of the final design changes drastically on relaxing this assumption. This becomes a necessity when the design is considered in greater detail and actual shells are determined. Cost estimation based on the individual-

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[1] It is assumed that shell and tube type heat exchangers are used. A unit is a composite assembly of TEMA shells. Shell in this thesis refers to a TEMA shell.

shell areas in an actual design leads to a proposal for an optimum design which is different to that obtained when assuming single-shell units. However, a final design with minimum number of *shells* and *units* is likely to be closer to the global optimum. Hence, a target for minimum number of shells should be set so that the design engineer has some guidelines to identify better designs.

The pinch-design method [100] advocates that a design with minimum number of units and maximum energy recovery (MER) is likely to be the optimum. Despite its simplicity and power, this heuristic is somewhat misleading. Comparison between the solutions of the celebrated literature problems reveals that multiple solutions exists satisfying these criteria but possessing different total annual costs. It is suggested that these differences can be resolved by basing cost estimation upon the number of shells required rather than the number of units. This is a more realistic procedure and has been neglected in the current design methodologies. Additionally, a method is proposed to achieve the targets for the minimum number of shells required by the network. The method developed is easy to implement and should enable the designer to quickly and confidently identify an optimum design.

Figure 3.1 illustrates the general trend of cost curves as a function of $\triangle t_{min}$. It can be shown that as the value of $\triangle t_{min}$ increases capital costs decrease and the operating (utilities) costs increase. Thus, there will be a value of $\triangle t_{min}$ for which the total annual cost of the network is minimum. Thermodynamic principles and the value of $\triangle t_{min}$ can be used to set targets for minimum heating and cooling utilities required for designing a network [100]. As the amount of utilities required is known, the *minimum* costs of the utilities (both hot and cold) can be calculated before synthesizing the network. However, capital cost cannot be estimated in advance of design and so the optimum value of $\triangle t_{min}$ cannot be determined prior to design. As a result, all the design approaches reported in literature follow the procedure outlined in Figure 3.2. A search is made over a range of $\triangle t_{min}$ values until the optimum is found. To minimize these iterations, it is necessary to identify as narrow a range as possible in which the optimum value of $\triangle t_{min}$ is likely to be found. Hohmann [56] and Ahmad [3] have reported the existence of techniques for estimating the value of $\triangle t_{min}$, but neither have provided details of their method. In this chapter, a

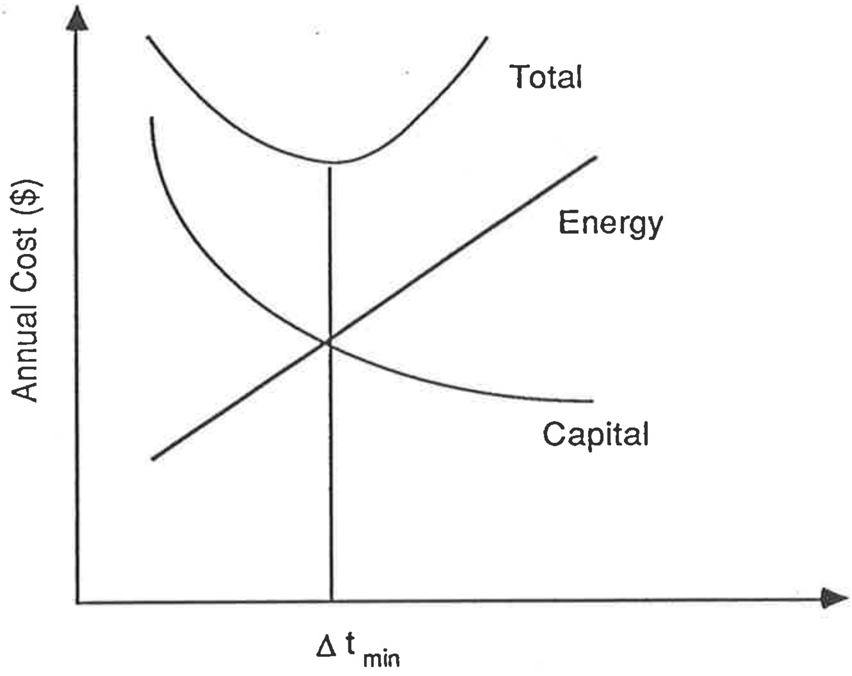


Figure 3.1: Cost curves in a HEN

straightforward and easily understood alternative method for the prediction of such Δt_{min} values is described.

Industrial problems often feature multiple pinch points. Systematic design rules have not been reported in current literature for the design of such problems. This chapter also discusses the MER network synthesis procedure for handling such problems.

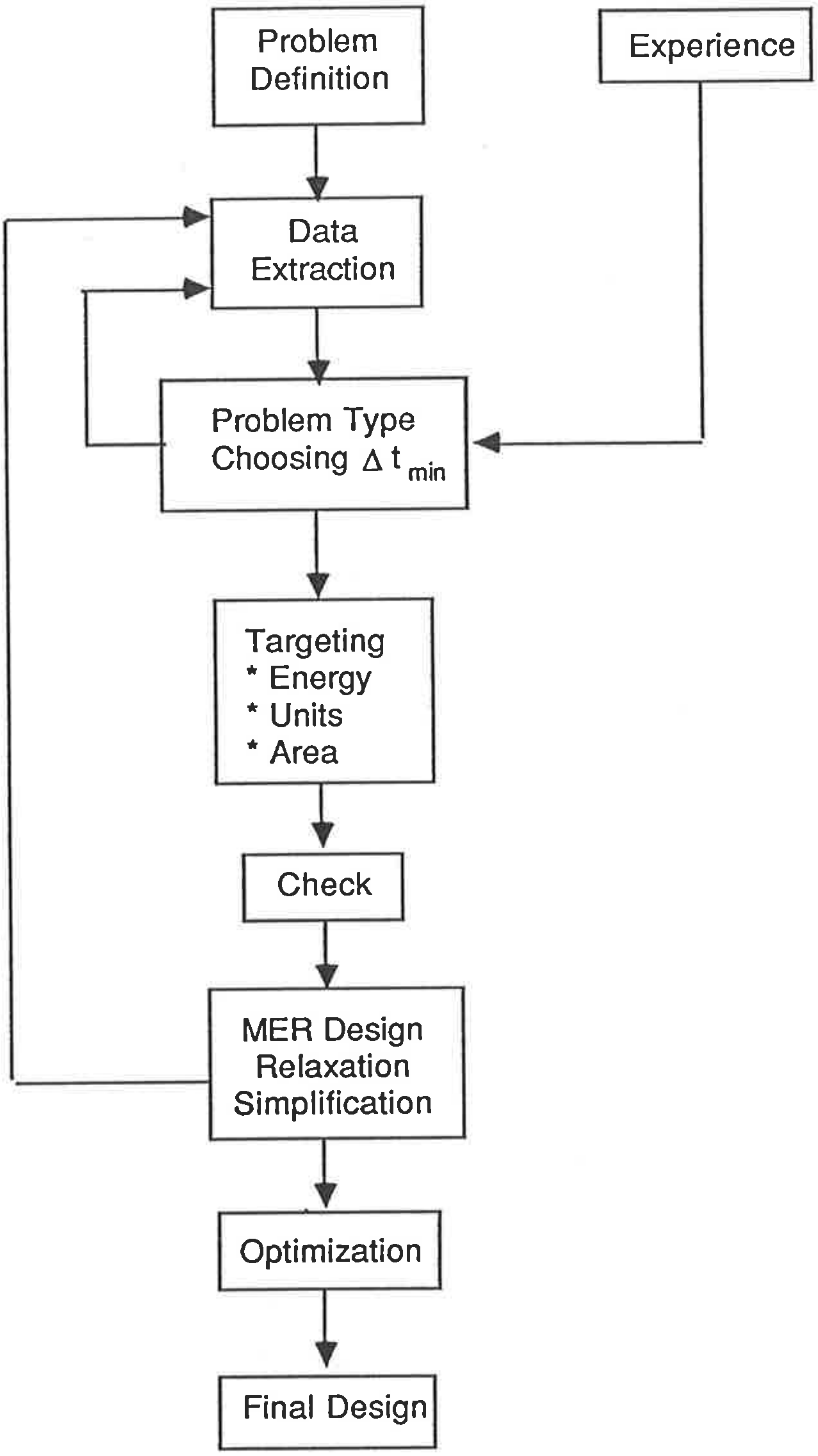


Figure 3.2: Existing overall design procedure [100]

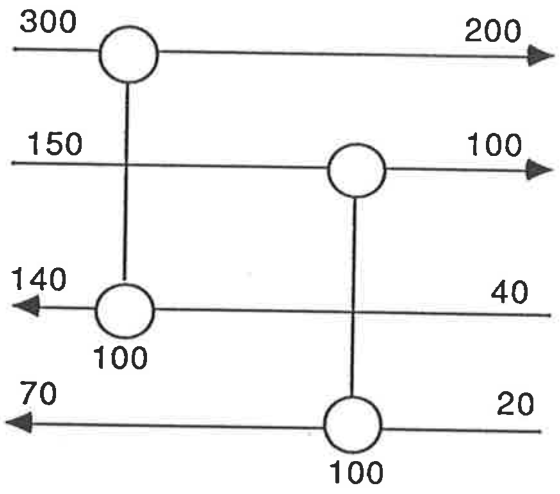
3.2 Shell Targeting

Targets can be set for minimum number of units, minimum utility consumption and minimum network area. Methods for finding these targets are well established [100,151]. However, methods for setting targets for the minimum number of shells have not been reported in literature todate. In this section, a systematic procedure for shell targeting is developed. This will provide a guide for final optimization of the network.

Consider a four stream problem, the networks for which are illustrated in Figure 3.3. For this problem, $U_{min} = 2$, as a subset equality exits. Two different designs with *two* units are possible. Network (a) requires only two shells, whereas network (b) requires four shells, as a consequence, the latter will have a greater capital cost. The difference in the number of shells between both the designs results from the different levels of temperature at which the exchangers are placed. **Hence, the minimum number of units can be predicted independently of the actual matches but the number of shells required in the network is dependent upon the stream matches.**

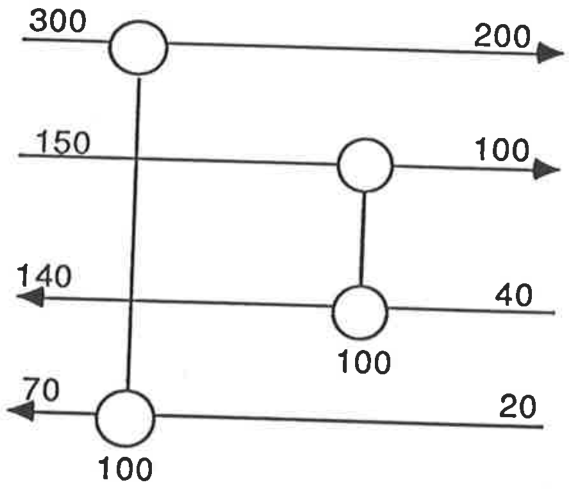
In Table 3.1, target values are reported for the number of units, number of shells (predicted using the method described below) and the minimum-area requirement for a variety of literature problems. The reported solution values for the problems are also included. The total annual cost of the solutions based on the area per unit and area per shell (calculated using equation 3.2 and equation 3.3 on page 50) are reported. A minimum LMTD correction factor of 0.8 was assumed for calculating the number of shells required by an exchanger. The cost data is tabulated in appendix A.

Two designs have been reported in literature for the well documented problem 4sp1 (Table 3.2). Design 1 [81] utilizes 5 units and 10 shells. Design 2 [56] has 5 units and 9 shells. Both these designs have minimum number of units and are maximum energy-recovery designs. The total area required by design 2 is less than design 1 and the cost, based on both shells and units, is less than design 1. Thus, a design which contains minimum number of units and features maximum energy recovery, may not



2 units, 2 shells
MER design

Network - (a)



2 units, 4 shells
MER design

Network - (b)

Figure 3.3: Networks for example 3.1

Table 3.1: Comparison of target values for units, shells, and area with the actual design values reported for literature problems

	Targets					Solutions			Costs x10^2	
Problem	Units	Shells	Area[1]	Design	Reference	Units	Shells	Area	Shell	Unit
4sp1	5	9	54	1	Lee (1970)	5	10	79	290	273
				2	Hohmann (1971)	5	9	66	282	268
4sp2	4	14	21	1	Linnhoff (1978)	7	14	30	259	217
				2	Nishida (1977)	6	16	27	260	204
				3	Linnhoff (1978)	4	15	36	273	199
				4	Linnhoff (1978)	4	18	28	270	195
5sp1	5	12	130	1	Masso (1969)	5	12	174	421	388
				2	Nishida (1977)	5	13	186	423	386
7sp1	7	16	217	1	Masso (1969)	8	18	290	1074	1021
				2	Linnhoff (1978)	7	16	277	996	946
7sp2	7	10	92	1	Linnhoff (1978)	7	10	109	297	282
				2	Masso (1969)	7	14	134	317	291
7sp4	8	26	28	1	Papoulias (1983)	10	25	36	7679	7582
10sp1	10	17	212	1	Nishida (1977)	10	19	276	1512	1419
				2	Linnhoff (1979)	10	19	255	1445	1406
				3	Linnhoff (1979)	10	21	271	1569	1522
				4	Su (1983)	10	18	254	1486	1449
				5	Papoulias (1983)	10	23	296	1513	1456

Table 3.2: Data for problem 4sp1 [81]

$\Delta t_{Emin} = 10$ K

Stream Number	C_p(kW/K)	T_s(°C)	T_t(°C)
c1	7.62	60	160
h2	8.79	160	93
c3	6.08	116	260
h4	10.55	249	138

necessarily be the optimum design. A similar situation exists for the problems 4sp2, 7sp2 and 10sp1. Problem 5sp1 provides an interesting example. The design based on criterion of number of units favours the solution of Nishida et al. [112]. However, for a shell based design, Masso and Rudd's [105] network, is shown to be optimal. From the above examples, it can be concluded that a design featuring *minimum number of units, minimum number of shells and whose total area is close to the minimum targeted area* is likely to be the optimum. It therefore seems apparent that a target for the minimum number of shells is required to readily identify the final optimum design. In the following section, a technique is developed for estimating the quasi-minimum number of shells required in a HEN.

3.3 Estimation of Number of Shells in a Heat-Exchanger Network

The balanced composite curves can be considered to be the " operating lines " for a network and may be used for shell targeting.

3.3.1 Estimation for Total Number of Shells Required by the Cold Streams

- Commencing with a cold stream target temperature a horizontal line is drawn until it intercepts the hot composite curve. From that point a vertical line is dropped to the cold composite curve. This section, defined by the horizontal line represents a single exchanger shell in which the cold stream under consideration gets heated without the possibility of a temperature cross. In this section, the cold stream will have at least one match with a hot stream. Thus, this section implies that the cold stream will require at least one shell. This procedure ensures an adequate logarithmic mean temperature correction factor as explained in Appendix B.
- Repeat the procedure until a vertical line intercepts the cold composite curve at or below the starting temperature of that particular stream.
- The number of horizontal lines will be the number of shells the cold stream is likely to require to reach its target temperature.
- Repeat the procedure for all the cold streams.
- The sum of the number of shells for all the cold streams is the total number of shells required by the cold streams to reach their respective target temperatures.

Problem 4sp1 will be used to illustrate the methods developed. Figure 3.4 shows the procedure for the cold stream 3, in problem 4sp1, which requires 5 shells. An analogous procedure can be utilized for the hot stream.

3.3.2 Estimation for Total Number of Shells Required by the Hot Streams

- Starting from the hot-stream initial temperature, drop a vertical line on the balanced composite curve until it intercepts the cold composite curve. From

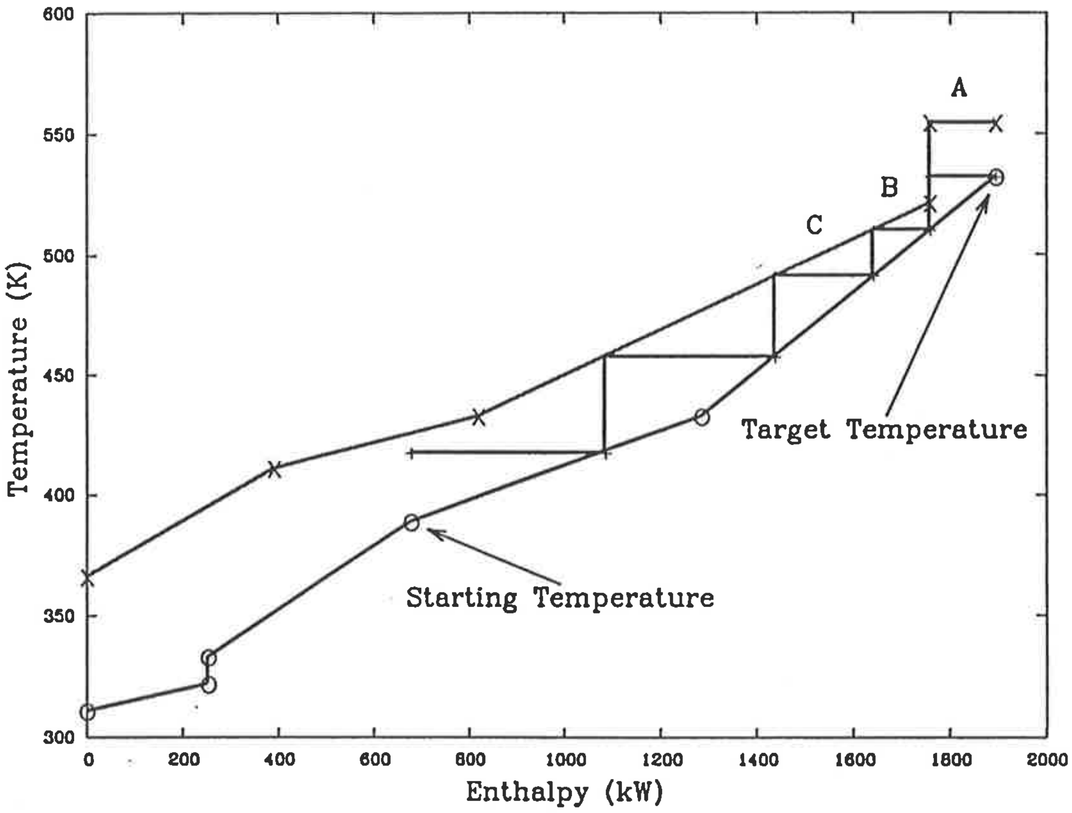


Figure 3.4: Shell target for the cold stream 3 of problem 4sp1

this point construct the steps in the form of horizontal and vertical lines until a horizontal line intercepts the hot composite curve at or below the hot stream target temperature.

- The number of horizontal lines will be the number of shells required by the hot stream for heat exchange in the network.
- Repeat the procedure for all the hot streams.
- The sum of the number of shells required by the hot streams will be the total number of shells required by the hot streams to reach their respective target temperatures.

The **quasi-minimum** number of shells required in the network would be the **maximum** of either the total number of shells required by the hot streams or the total number of shells required by the cold streams. Bell [12] has reported a similar procedure for estimating the number of shells required in a heat exchanger. Ahmad et al. [1] have proposed an analytical method for finding the number of shells in a single unit. Their method is based on the stepping-off procedure of Bell. Details of how their method is applied for shell targeting in heat exchanger networks has not been reported.

This procedure, for large values of $\triangle t_{min}$ may predict the *quasi-minimum number of shells* less than the *minimum number of units for a maximum energy recovery network.* Hence, the target of minimum number of units for a MER network should be used as a lower bound for quasi-minimum number of shells. Application of this method to a variety of problems has resulted in prediction of the minimum number of shells to an accuracy of plus/minus one shell (see Table 3.1).

3.4 Synthesis of Multipass Heat Exchanger Networks

In the previous section, a method for establishing a shell target was proposed. Here a new factor has been developed to help in achieving the above shell target in a

MER network. The synthesis is carried out by employing the pinch design method. Whenever a decision has to be made between matching options, the proposed factor shall be used for the selection of a match.

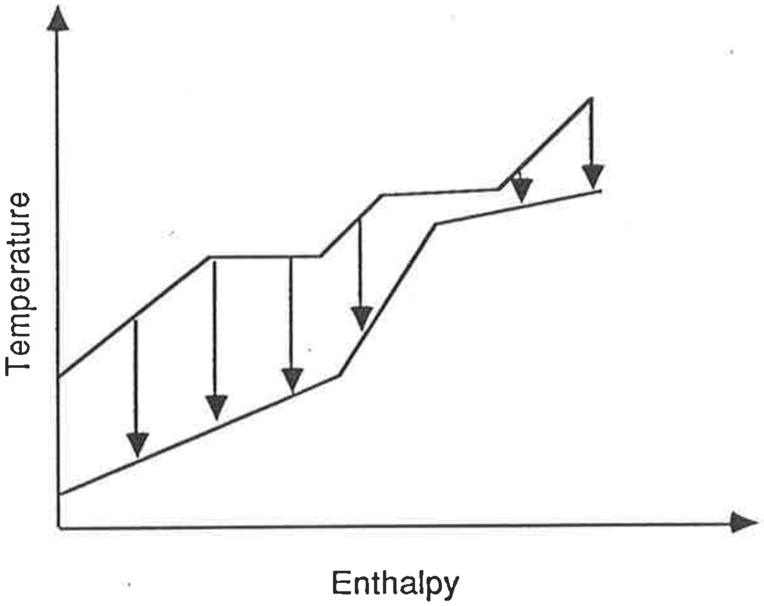
The procedure for calculating the target number of shells required in a HEN assumes that there will always be a match in the horizontal section which defines a shell on the composite curves. Consider a stage for a cold stream as shown in Figure 3.4. In the final design, a hot stream from section A might be matched with a cold stream in section B or a hot stream of section C may be matched with a cold stream in section B. To achieve the shell target, it is necessary that a hot stream in section B is matched only with a cold stream in the same section. This implies that the matches should be placed '*vertical*' against the composite curve. A 'vertical heat transfer' [151] takes place in the network if all the matches are placed vertical against the composite curve. Such a network will have minimum area as the temperature potential is properly distributed among all the matches. However, in the final design matches are seldom vertically placed resulting in a 'criss-cross' heat transfer taking place in the network (see Figure 3.5). In such a situation, the temperature potential is not properly utilized resulting in the use of excess area and number of shells. To quantify this criss-cross phenomena, a scalar function 'criss-cross factor' is defined as

$$ccf = \frac{\triangle t_a - \triangle t_v}{\triangle t_v} \times 100 \tag{3.1}$$

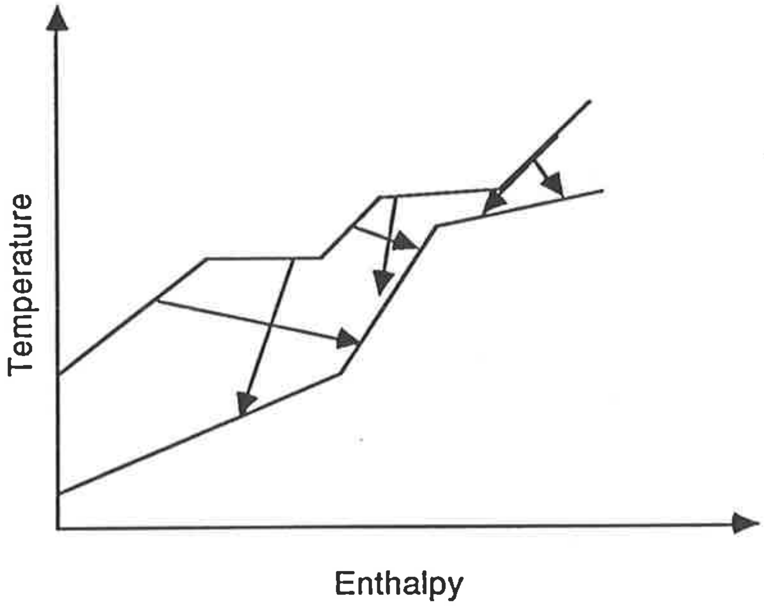
where,

ccf	is the criss-cross factor,
$\triangle t_v$	is the LMTD if the exchanger is vertical when placed against the composite curves,
$\triangle t_a$	is the actual LMTD of the exchanger in the network.

The value of $\triangle t_v$ can be evaluated based on either the change in the hot stream



(a) Vertical heat transfer



(b) Criss-crossed heat transfer

Figure 3.5: Vertical and criss-cross heat transfer [151]

temperature or the cold stream temperature. To illustrate the calculation of the value of $\triangle t_v$, consider an exchanger match for the problem 4sp1 in which the hot stream is cooled from 160°C to 93°C and the cold stream is heated from 60°C to 137°C. Hence, the value of $\triangle t_a$ is 27.7 K. If this match was placed vertically against the composite curves, the LMTD will be 58.25 K. Thus, the ccf based on hot stream for this match would be -52.45. The cold stream can also be used as the basis for calculation in a similar way. In the following discussion the value of ccf will be based on the hot stream temperature of the match.

The sign of ccf gives a good indication of the effect of the match on the deviation from the concept of vertical heat transfer. It also indicates which exchangers are responsible for the excess area used in the network. A negative value of the factor indicates that the temperature potential is not properly utilized and so extra area is required for the match. Furthermore, such a match may be responsible for the usage of extra shells in the network. A positive value indicates that excess temperature potential is used and so less area and number of shells may be used for the match. Hence to achieve the targets, matches should be placed in such a way that the absolute value of ccf is near zero.

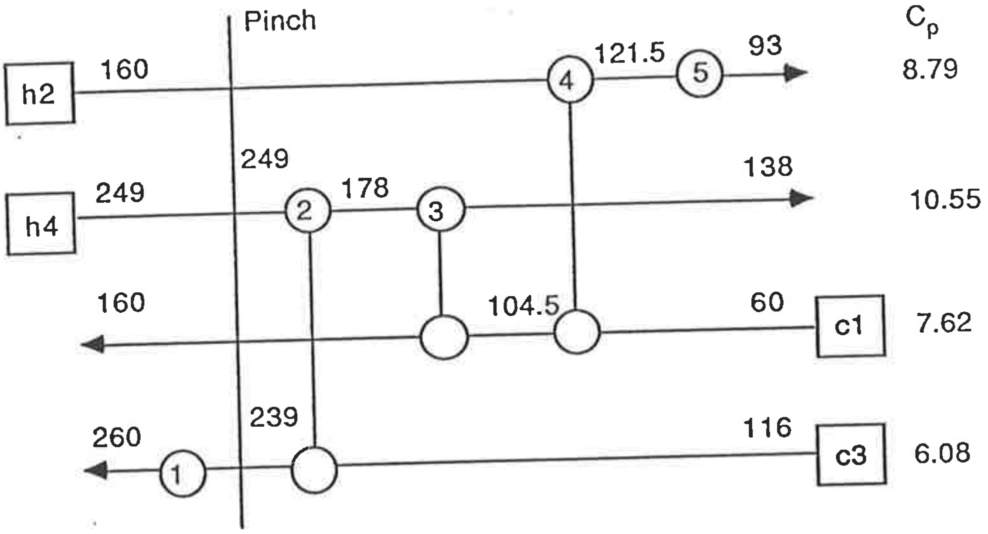
This factor will now be used to illustrate the synthesis procedure by solving the problem 4sp1. For this problem, the pinch point is 249°C-239°C. The network above the pinch point consists only of a heater. There is only one pinch match below the pinch point. This match cools the hot stream 4 to 178°C. For designing the remaining network no guidelines are avaliable. Two options are possible. First, stream 4 is matched with stream 1 to satisfy stream 4 and then stream 2 is matched with stream 1. The second option is to match stream 2 with stream 1 to 'tick-off' stream 2 and then match stream 4 with stream 1. The resulting topologies are illustrated in Figure 3.6. For option 1 the values of ccf for unit 3 and 4 is -47.43 and 26.9 respectively. For option 2 the value of ccf for unit 3 and 4 is -40.91 and -52.45 respectively. From these values the designer can make the appropriate judgement for selecting the matches. Unit 3 in both the design option has approximately the same value of ccf. However, unit 4 in design option 1 has the value of ccf closer to zero and so this option is selected. This option is in/fact the optimal design with the target number of shells and the least area network.

Liu et al. [103] have proposed an iterative method for synthesizing multipass heat exchanger networks. Their method solves the problem initially as one which employs only single-pass services by using the thermo-economic approach of Pehler and Liu [120]. Secondly, with the resulting heat transfer areas of single-pass services, the minimum-cost multipass services, which achieve the same design objectives (with the same values of the heat capacity ratio and thermal efficiency) are located by finding the required number of shells and the LMTD correction factor.

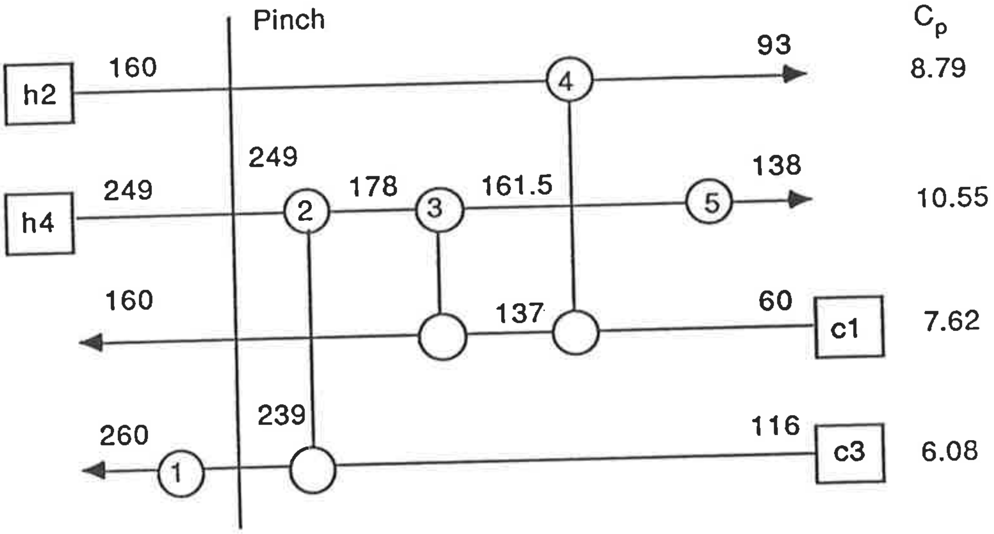
Linnhoff and Vredeveld [90] have proposed the use of the $\Delta t/t_c$ curve. Their method would give similar results, but the matches are placed by the designer on his judgemental value and intuition. The proposed method removes this limitation by employing a quantitative factor which helps in evaluating the different options.

3.5 Capital - Energy Trade Off in Heat Exchanger Networks

Figure 3.1 shows the general trend of the cost curves observed in the design of a heat-exchanger network. Ahmad and Linnhoff [3] have observed that the actual cost profiles have discontinuities, illustrated in Figure 3.7. The complex nature of the actual profiles results from the change in number of *units* with respect to Δt_{min}. This in turn has a very strong influence on the capital cost of the network. They have reported that as the value of the Δt_{min} changes, the stream determining the pinch point likewise changes and discontinuities are observed. This is shown as Figure 3.8 in the energy-targeting plot, the area-targeting plot [151] and the units-targeting plot. Based on the above observations and certain simplifying assumptions (e.g. to combine the minimum area targets and minimum number of units target), Ahmad and Linnhoff [3] proposed that the optimum value of Δt_{min}, depending on the rate of return, will be located at one of the discontinuities in the targeting curves. In this analysis it was assumed by Ahmad that each unit would be a single-shell exchanger.



(a) Option 1 (Hohmann's design)



(b) Option 2 (Lee et al.'s design)

Figure 3.6: Different topologies for problem 4sp1

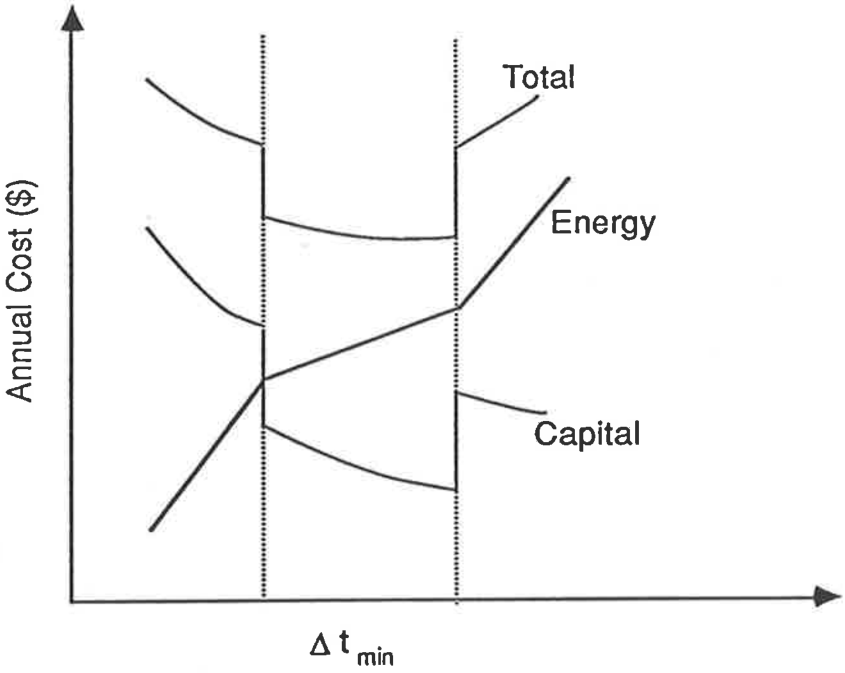


Figure 3.7: Actual Cost curves in a HEN [3]

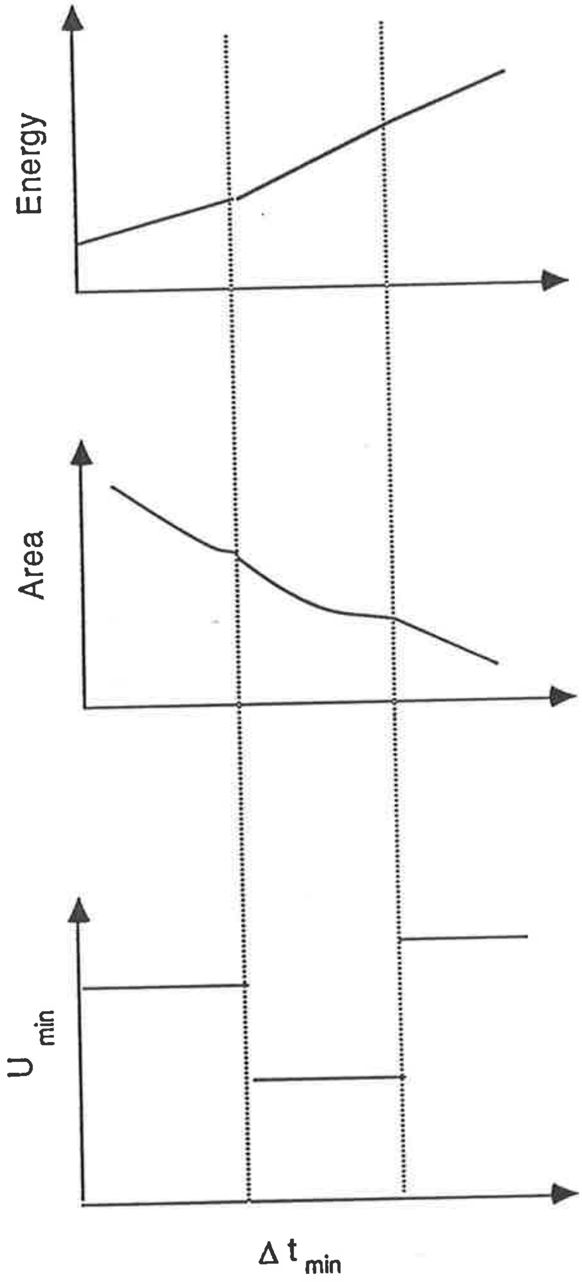


Figure 3.8: Targeting plots for a HEN [3]

Problem 4sp1 was analysed using the above procedure. The 'kinks' in the energy-targeting plot are found when $\triangle t_{min}$ = 58 K and 133 K. (Ahmad's description does not consider the possibility of a discontinuity existing at $\triangle t_{min}$ = 0 K.) Hence, by Ahmad's method the predicted value of the optimum $\triangle t_{min}$ will be in the vicinity of 58 K or 133 K. Actual maximum energy-recovery (MER) networks designed for different values of $\triangle t_{min}$ using the *pinch-design method* for the same problem suggest that the above predicted optimum is in fact near zero. Obviously, a practical limit will exist, eg. a value of $\triangle t_{min} \geq 5$ K might be reasonable, but any method proposed should be capable of detecting such situations.

The set of annual total costs for problem 4sp1 were obtained using equation 3.2 and are presented as Figure 3.9.

$$C_u = i \times \sum_{k=1}^{N_{unit}} aA_{u_k}^b + C_{utility} \tag{3.2}$$

The minimum-cost network for an actual *design* was found to have a value less than 3 K. However, as stated above it is assumed that a value of $\triangle t_{min}$ equal to 5 K would be the lowest practical value for the network to be operable.

The cost curves (calculated using equation 3.3)

$$C_s = i \times \sum_{k=1}^{N_{shell}} aA_{s_k}^b + C_{utility} \tag{3.3}$$

for the same designs based, however, this time on the individual-shell areas and actual number of shells used in the final design, are shown in Figure 3.10. The optimum value of $\triangle t_{min}$ is found to be 8 K. This is considered to be a more realistic optimum as it takes into account the total number of shells used in the final design. This would also seem to be a more realistic value from the point of view of general experience.

It would seem therefore that Ahmad's method may have two limitations. First, the assumption that the theoretical optimum will not be near zero, and second,

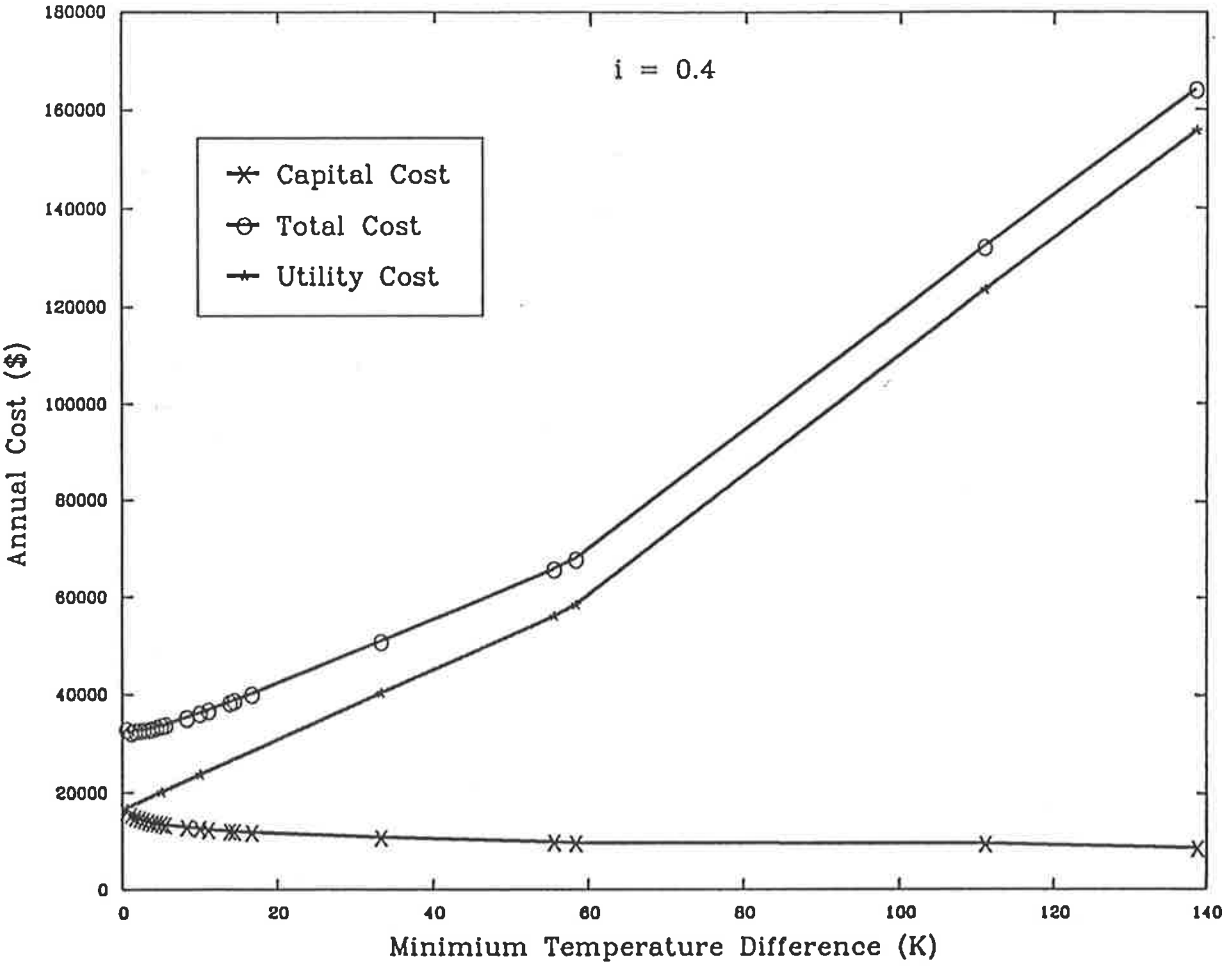


Figure 3.9: Cost curves for problem 4sp1 based on area of a unit

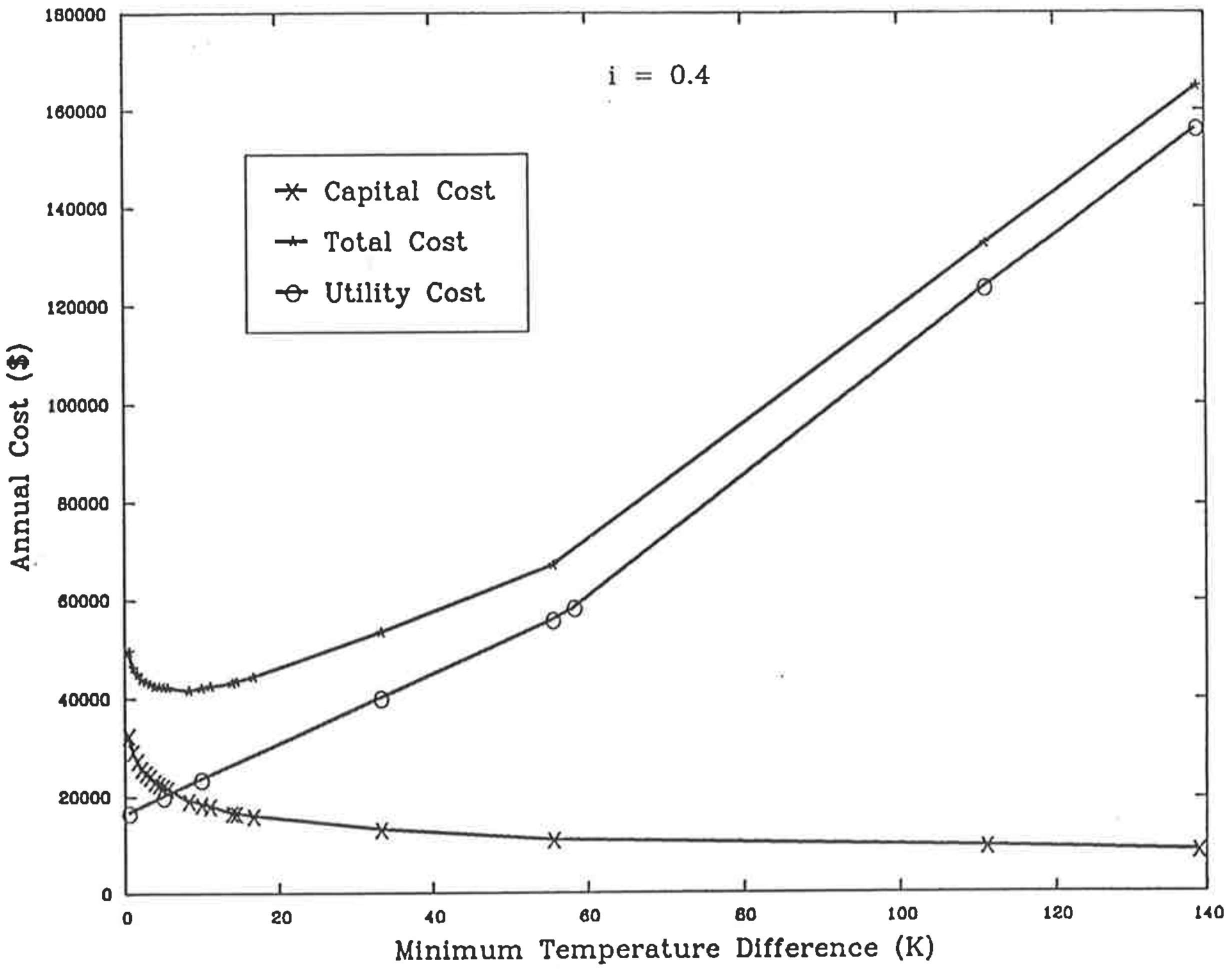


Figure 3.10: Cost curves for problem 4sp1 based on the area of a shell

that *each unit is a single-shell exchanger* rather than considering the possibility of multiple-shell exchanger units with the consequent effects on capital cost.

A new method is proposed to remove these drawbacks. Traditionally, the simplifying assumption utilized is that capital cost can be estimated by some (unspecified) combination of predicted minimum area and minimum number of units. Here, it is proposed that the capital-cost estimation be based on an ' actual ' design. In this design, the total area is minimum. The number of units used represents the lower bound (quasi-minimum) to the maximum number of units and at the same time satisfies the minimum-area target (predicted using initial estimates of individual stream heat transfer coefficients [151]). Each unit in this ' superstructure ' will be *designed* to be an actual single-shell exchanger. With this approach, a relatively narrow range for the optimum value of $\triangle t_{min}$ can be located, as illustrated in Figure 3.13. The capital cost for a design based on quasi-minimum number of single-shell exchangers for achieving minimum area in the network will be quite different from the final design which normally has minimum number of units. However, the shape of the cost curves would be expected to be similar for both the ' superstructure ' and the final design. Hence, the cost profile obtained by the proposed method for different values of $\triangle t_{min}$ would yield a narrow range for locating the optimum $\triangle t_{min}$.

3.5.1 Quasi-Minimum Number of Exchangers for Achieving Minimum Area and the Superstructure

For the proposed approach, the balanced composite curves (composite curves which includes the utilities) are divided into sections as shown in Figure 3.11. The procedure is as follows:

> On the balanced composite curves, starting with highest cold-stream temperature a horizontal line is drawn to intercept the hot composite curve. A vertical line is then drawn to intercept the cold composite curve. This procedure is repeated until a horizontal line crosses the left

hand ordinate. Vertical lines are also drawn at the 'kink' points on the balanced composite curve. Each horizontal line between two adjacent vertical lines then represents a section for vertical matching of streams.

In any of the above sections, the composite-stream enthalpy balances are satisfied and the target hot-stream temperature is equal to or greater than the target cold-stream temperature, hence any exchanger match placed in that section will require a single-shell only (refer to Appendix B). A sub-network can then be designed for each section in which all exchanger units have a single shell. The minimum number of units in the sub-network for each section can be found by using Euler's theorem (see equation 2.5) [100].

The quasi-minimum number of single shell exchangers for achieving minimum area for the whole network is then given by

$$S_{min} = \sum_{j} U_{min_{sec_j}} \tag{3.4}$$

The network generated using the above procedure is called the " superstructure ". The area target reported in Table 3.1 are calculated from the superstructure design for the problem under consideration. This superstructure can then be used as a consistent basis for relative capital-cost estimation and comparison. The above algorithm can be easily programmed and then used to estimate the relative capital cost of the network for different values of $\triangle t_{min}$. The prime objective of performing these cost predictions is to obtain a close estimate for the optimum $\triangle t_{min}$ for the final network, not to produce accurate final capital-cost estimates.

The superstructure for problem 4sp1 when $\triangle t_{min} = 11$ K is illustrated in Figure 3.12. Figure 3.13 displays the results for cost estimation when this procedure is applied to problem 4sp1. The optimum $\triangle t_{min}$ value found is nearly equal to the actual final-design value. Figure 3.14 shows how the quasi-minimum number of exchangers for achieving minimum area and the targeted quasi-minimum number of shells (discussed in the previous section) change with respect to $\triangle t_{min}$. The

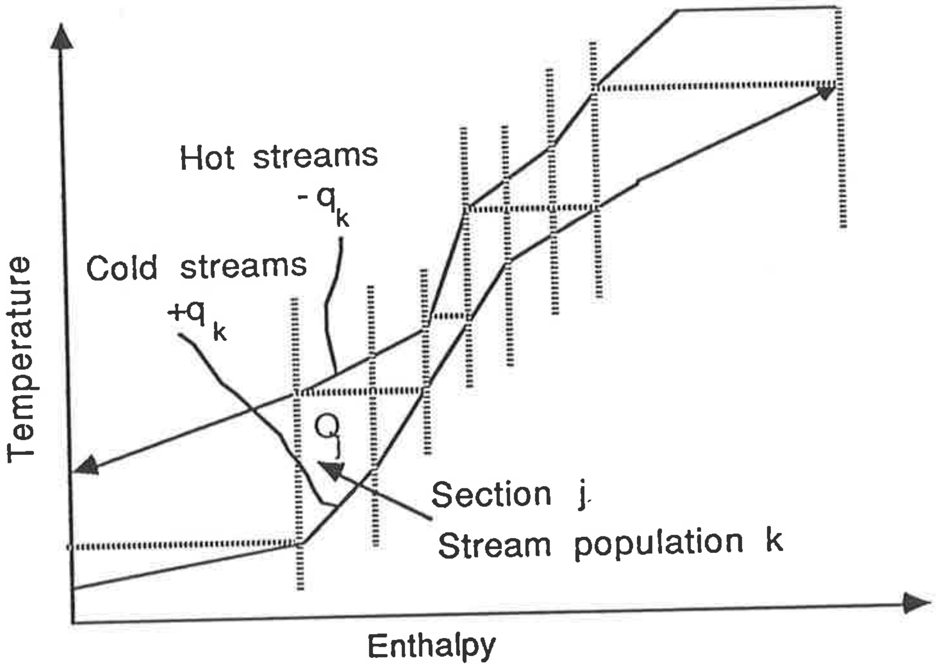


Figure 3.11: Sections for generating the superstructure

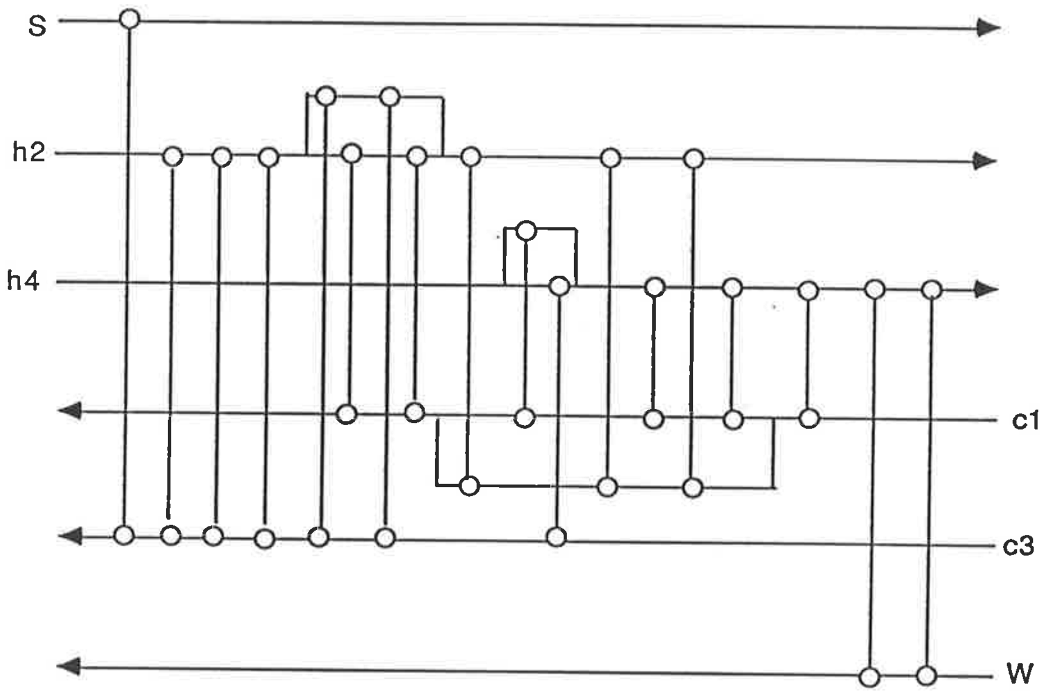


Figure 3.12: Superstructure for the problem 4sp1

quasi-minimum solution is one that is close to but not necessarily the optimum. The erratic nature of the changes in the quasi-minimum number of single shell exchangers for achieving minimum area with respect to $\triangle t_{min}$ is due to the phenomenon of " stream slipping " [3] which results in changes in the number of sub-networks for the particular pair of composite curves being considered. These changes are reflected in the cost curve " noise " and the effects may be amplified if subset equalities appear or disappear in the process.

From Figure 3.13 and Figure 3.14, it can be noted that the optimum lies in the region where the quasi-minimum number of shells change with respect to $\triangle t_{min}$ in a stepwise discontinuous fashion. Therefore, these points of discontinuity (viz. the $\triangle t_{min}$ values) provide a useful starting point for initial " superstructure " construction. The same result has been observed with several other problems under study. Thus, a method has been developed, which shows considerable promise for the minimization of total design effort in the global optimum design of heat-exchanger networks.

Recently, Linnhoff and Ahmad [102] have proposed a SUPERTARGET computer program for finding the optimal global value of $\triangle t_{min}$. However, they have not given enough details so that the proposed method can be compared with it. The same value for the optimum $\triangle t_{min}$ is obtained by the method presented here for the problem reported by them.

3.6 Synthesis of Heat Exchanger Networks Featuring Multiple Pinch Points

The pinch design method can quickly identify the possible different solutions for networks having a single pinch point. Often, industrial problems feature multiple pinch points. This may be due to the use of multiple utilities employed at different temperature levels or phase change of process streams taking place. (An ethylene plant is reported to have five pinch points [99]). The composite curves [100] for

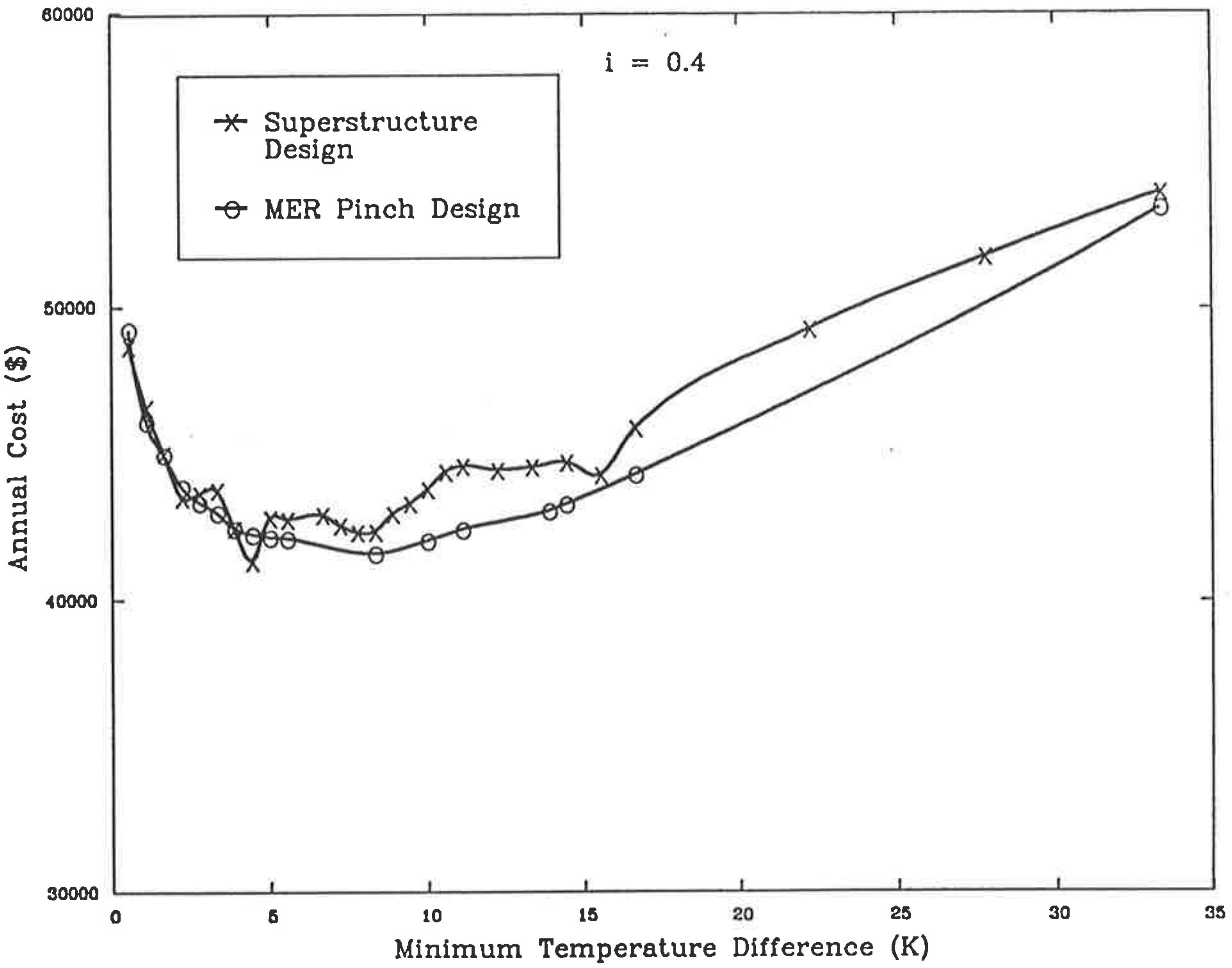


Figure 3.13: Comparison of actual and predicted costs for problem 4sp1

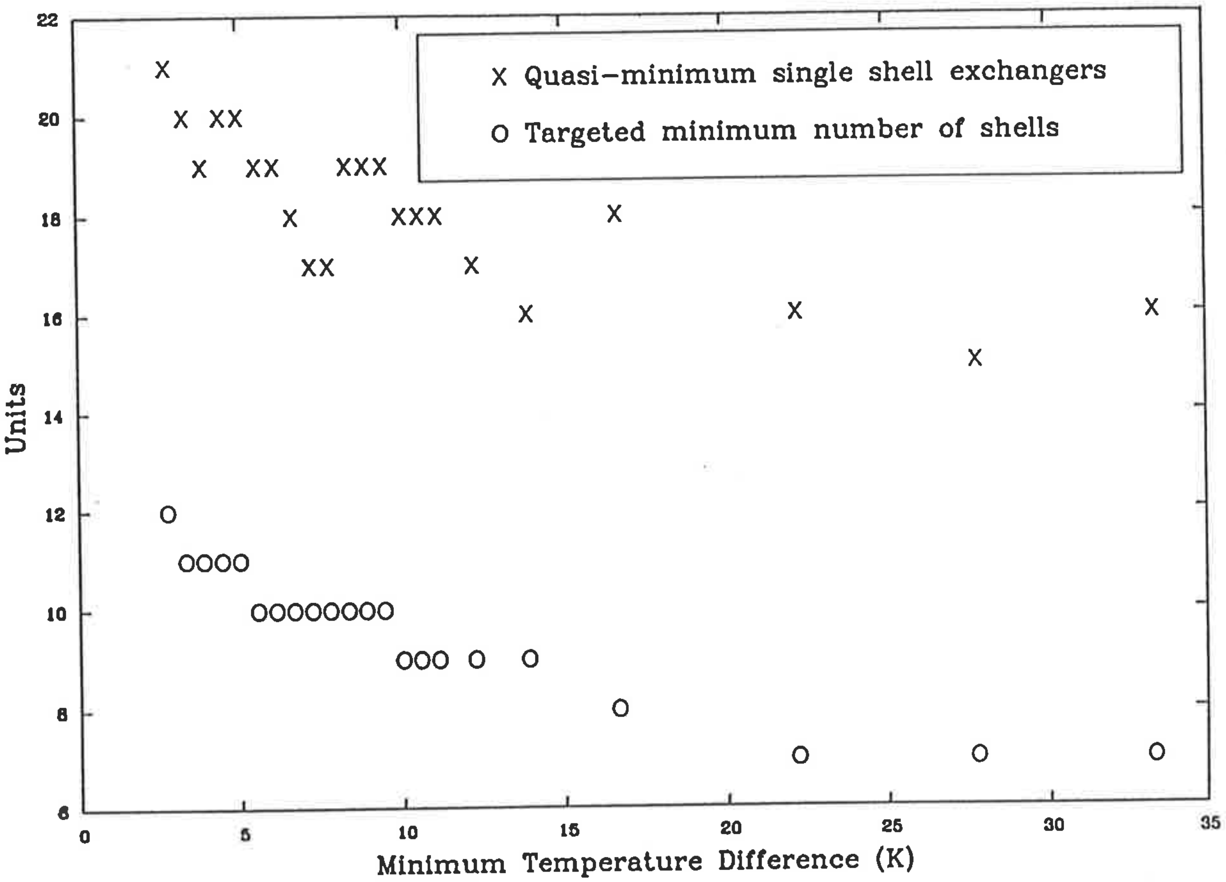


Figure 3.14: Quasi-minimum number of shells and exchangers for problem 4sp1

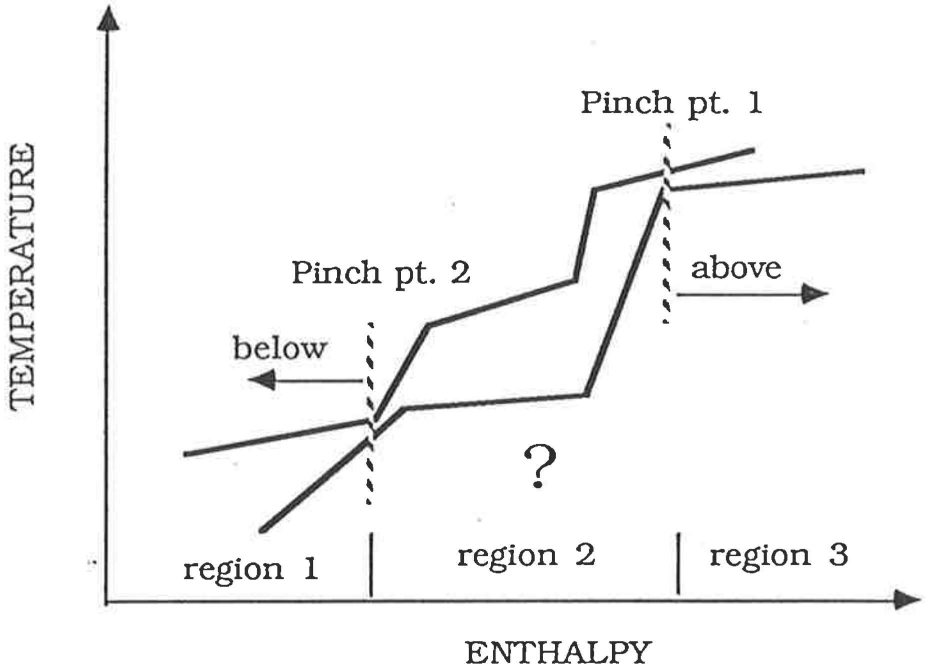


Figure 3.15: Composite curves with multiple pinch points

multiple pinch points is shown in Figure 3.15. This pair of composite curves feature two pinch points. The original problem, according to the pinch division philosophy, is now divided into three subproblems. Design of regions 1 and 3 can be undertaken using the pinch design rules. However, an ambiguity exists for region 2. Since the pinch design method advocates to start the design at the pinch, designing from either pinch points can lead to a " clash ". If region 2 is designed starting from pinch point 1 then below pinch rules have to be employed. On the other hand, if the design is started from pinch point 2, region 2 will be designed using above pinch rules. To avoid this " clash ", Linnhoff et al. [100] recommend to start the design at the most constrained pinch first. But, no guidelines are reported to identify this " most constrained pinch point ". Furthermore, this heuristic does not help the designer to systematically design for a region in-between adjacent pinch points. Clearly, new design guidelines are required.

Rév and Fonyó [128] have developed an algorithm which combines the pinch design

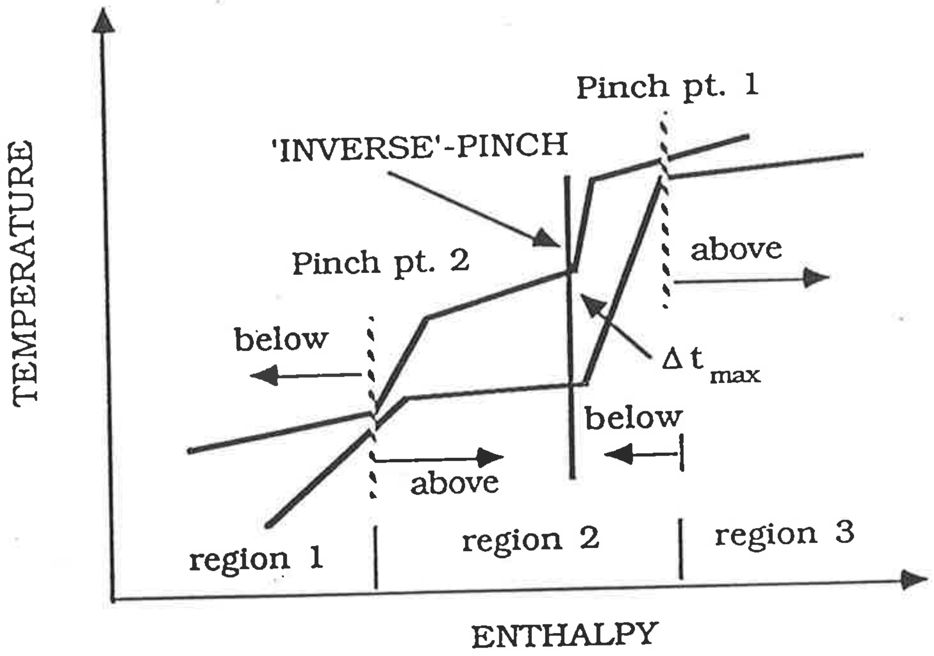


Figure 3.16: Composite curves with multiple pinch points and the 'inverse' pinch point

method and the algorithm proposed by Ponton and Donaldson [124]. This algorithm identifies the presence of hidden and pseudo pinch points and uses a computer for synthesizing the network. They claim to have successfully applied it to industrial scale problems. Here a further new division of the problem is proposed so that the existing pinch design rules can be employed.

3.7 The 'Inverse' Pinch Point

Consider the composite curves illustrated in Figure 3.15. The region 2 can be subdivided at the point such that below it

$$\sum C_{p_h} > \sum C_{p_c}$$

and above it

$$\sum C_{p_h} < \sum C_{p_c}$$

As these conditions are inverse of those at any pinch point, this point shall be referred as the ' inverse ' pinch point. Furthermore, this point features $\triangle t_{max}$ in region 2 on the composite curves as illustrated in Figure 3.16. Identification of this division leads to the removal of the existing ambiguity. Now, the region 2a can be designed using the above pinch rules. Similarly, the region 2b can be designed using the below pinch rules. The division of the synthesis problem at the ' inverse ' pinch point will increase in the total number of units in the initial network but it simplifies the design procedure. The number of units may then be reduced employing the algorithm proposed in the next chapter.

If the dual-temperature approach design method (this design method employs different values for the global network $\triangle t_{N_{min}}$ and the exchanger $\triangle t_{E_{min}}$) proposed in chapter 5 is used then the resulting 'pseudo-pinch' points and the 'pseudo-inverse-pinch' points should be modified in a consistent manner.

3.8 An Industrial Problem

To illustrate the above method consider the stream data tabulated in Table 3.3 of a gasoline fractionating plant given by Rév and Fonyó [128]. This problem has one pinch point at 155.5 °C/135.5 °C assuming a $\triangle t_{min}$ = 20 K. A near pinch situation exists due to the entrance of streams 8 and 9 at 97.5 °C. Thus, this problem can be treated as a multiple pinch point problem. The ' inverse ' pinch point occurs at 154.5 °C/ 96.5 °C. Assuming no constraints, an maximum energy recovery design is illustrated in Figure 3.17. This design has 25 units and 3 stream splits at two different places in the network. The design with relaxed energy, which can be further simplified depending on economics, is illustrated in Figure 3.18. It has an energy penalty of 3122 kW, 2 stream splits and 23 units. This design is more elegant and controllable then the design proposed by Rév and Fonyó [128] illustrated in Figure 3.19. Their design has 29 units, 5 stream splits and has an energy penalty of 5053 kW. The design illustrated in Figure 3.19 is unusual as a stream already split is further split thus making it very difficult to control the network.

3.9 Conclusions

- A method for delineating a small range in which the optimum value of $\triangle t_{min}$ is located has been described. The method involves specification of a " superstructure ". The " superstructure " consists of quasi-minimum number of single-shell exchangers for achieving minimum area and is used as a basis for relative cost estimation and comparison. Shell-targeting techniques have been shown to help in localizing this optimum. A global optimum value of $\triangle t_{min}$ can then be found close to the actual optimum $\triangle t_{min}$ for the final design network.

- The pinch-design method cannot be used in a similar fashion for cost estimation and hence for locating the optimum $\triangle t_{min}$, as the network so designed has at times total area more than 100 % in excess of the targeted minimum [151].

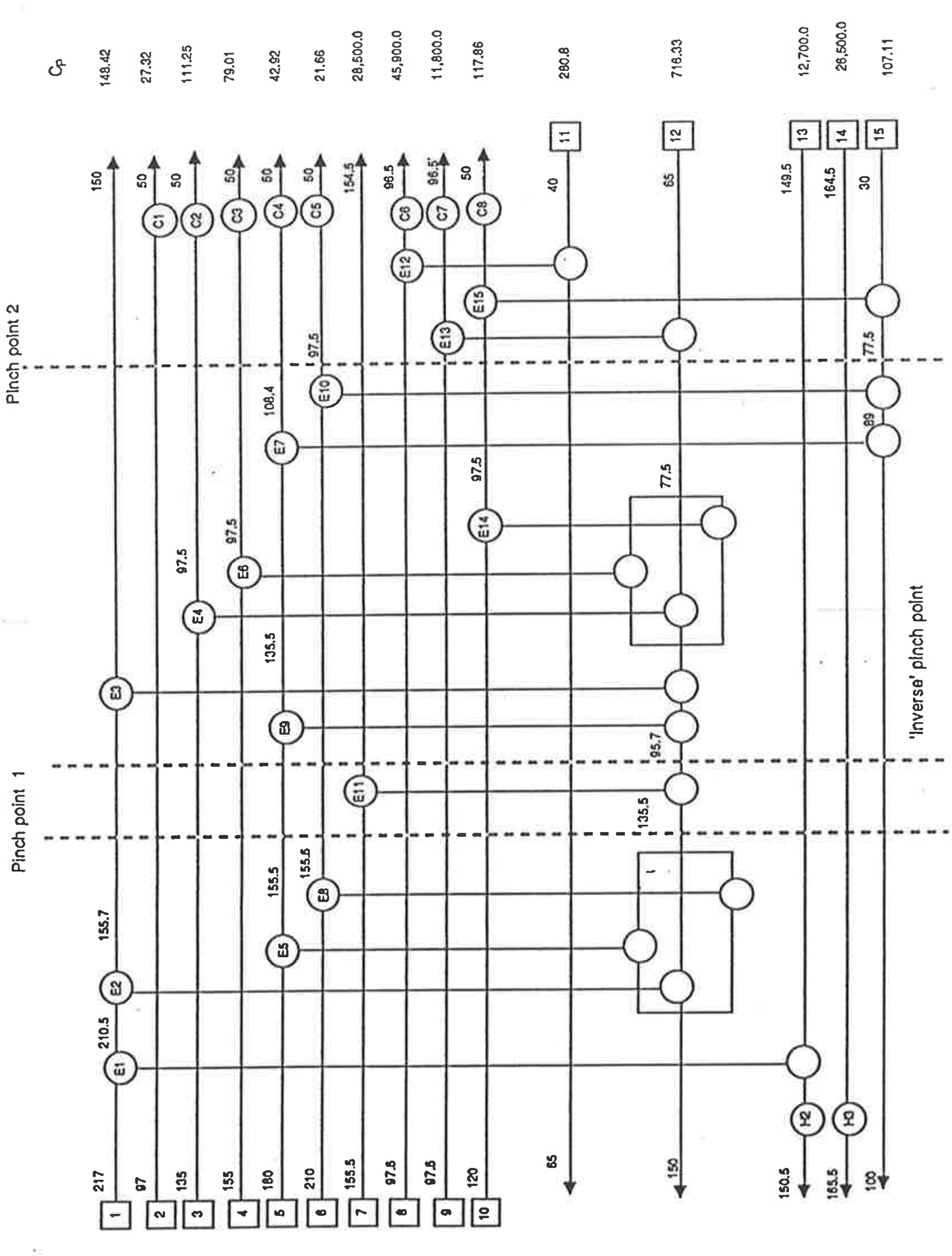


Figure 3.17: MER design for the gasoline fractionation plant

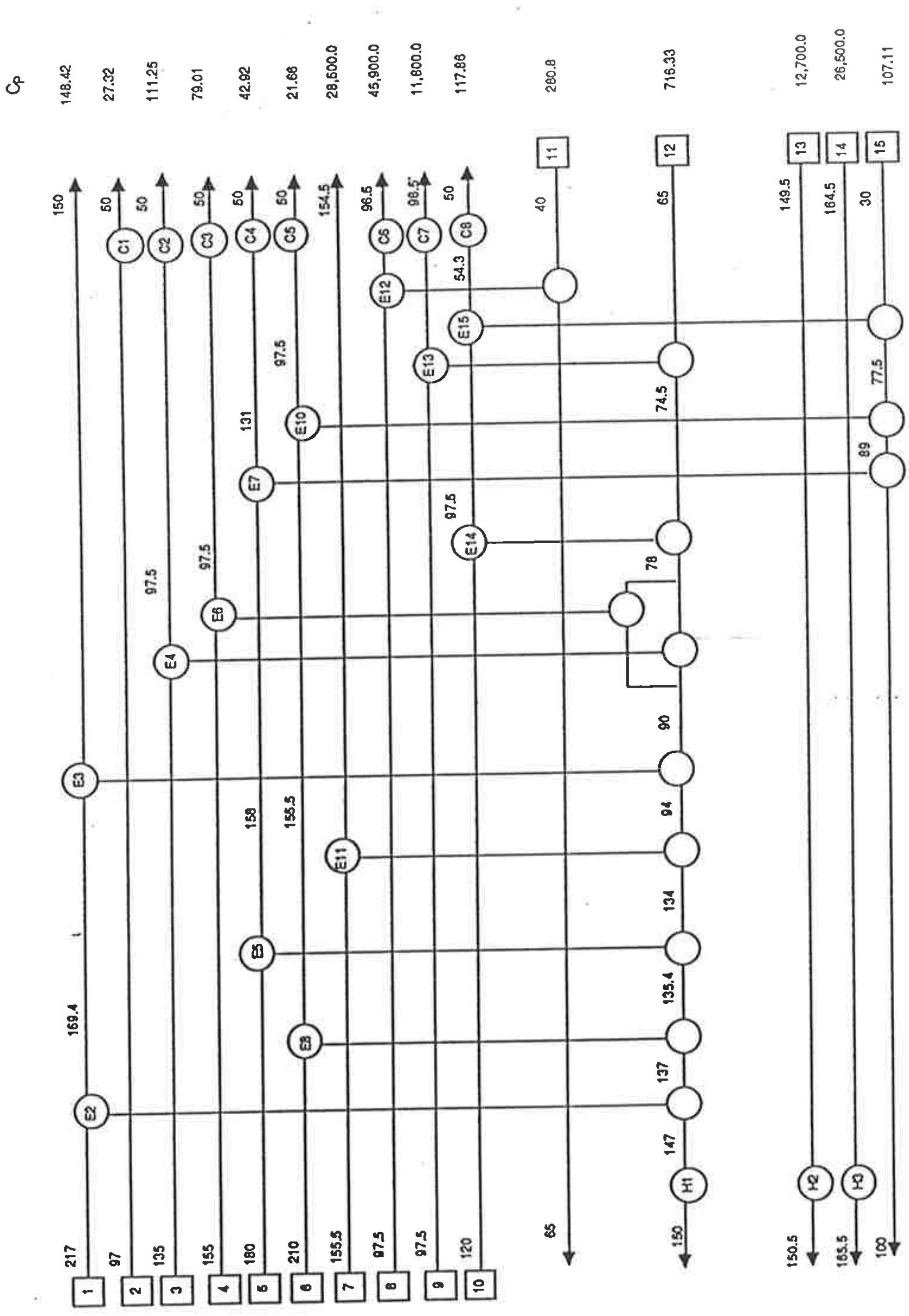


Figure 3.18: Relaxed design for the gasoline fractionation plant

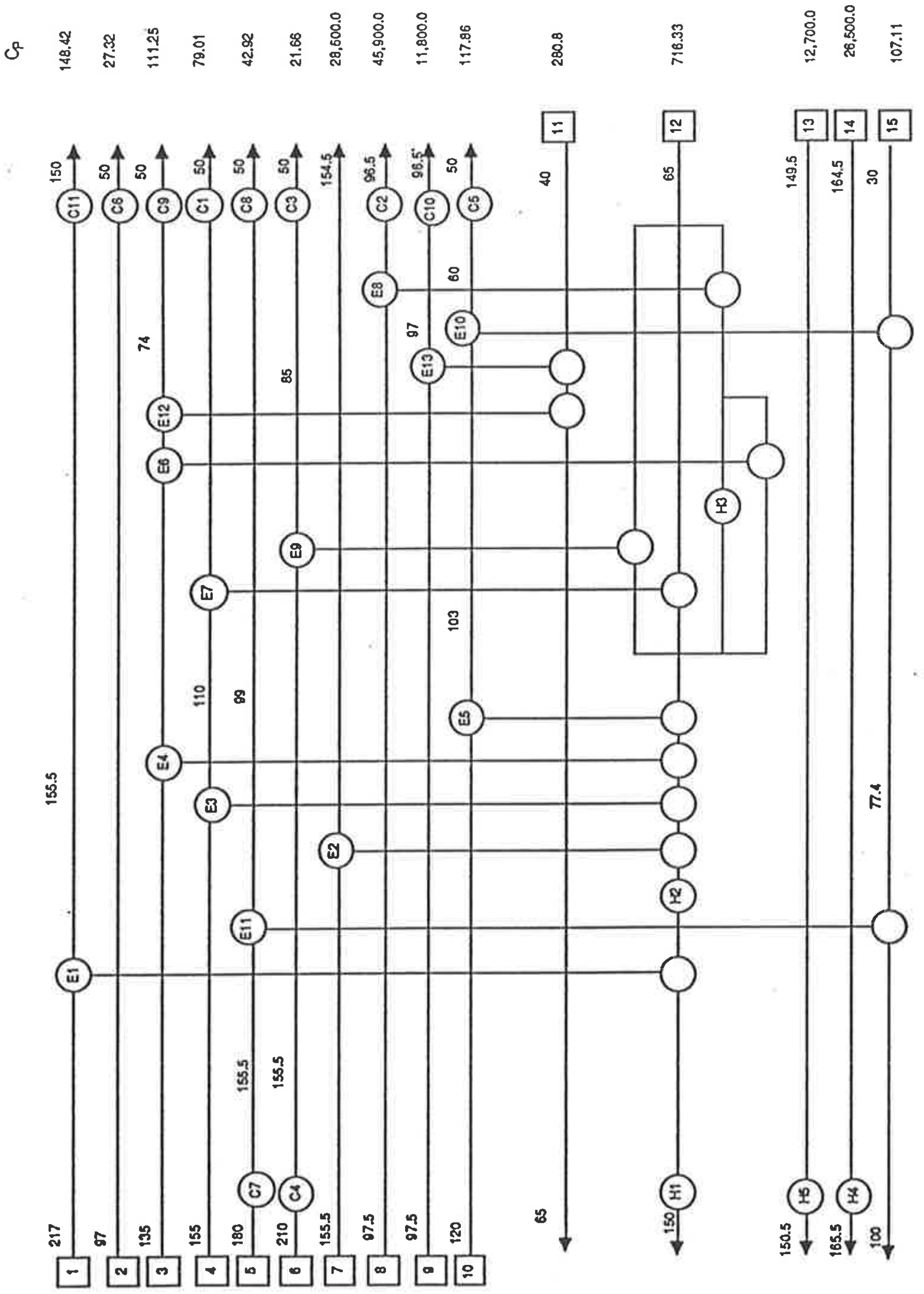


Figure 3.19: Rév and Fonyó's design for the gasoline fractionation plant [128]

Table 3.3: The gasoline fractionating plant problem [128]

Stream	T_s °C	T_t °C	C_p kW/K
1	217.0	150.0	148.42
2	97.0	50.0	27.32
3	135.0	50.0	111.25
4	155.0	50.0	79.01
5	180.0	50.0	42.92
6	210.0	50.0	21.66
7	155.5	154.5	28500.0
8	97.5	96.5	45900.0
9	97.5	96.5	11800.0
10	120.0	50.0	117.86
11	40.0	65.0	280.80
12	65.0	150.0	716.33
13	149.5	150.5	12700.0
14	164.5	165.5	26500.0
15	30.0	100.0	107.11

- The errors in cost estimation for the superstructure method are relative and so their effect on the predicted optimum $\triangle t_{min}$ is minimal.

- Individual film coefficients rather than overall coefficients are utilized for improved prediction of individual exchanger performance.

- The existing pinch-design methodology (illustrated in Figure 3.2) has been modified and improved. The new algorithm is summarized in Figure 3.20. The simplifications should result in savings in design time. Futhermore, new design methodologies have been proposed to achieve the set targets and to handle multiple pinch situations.

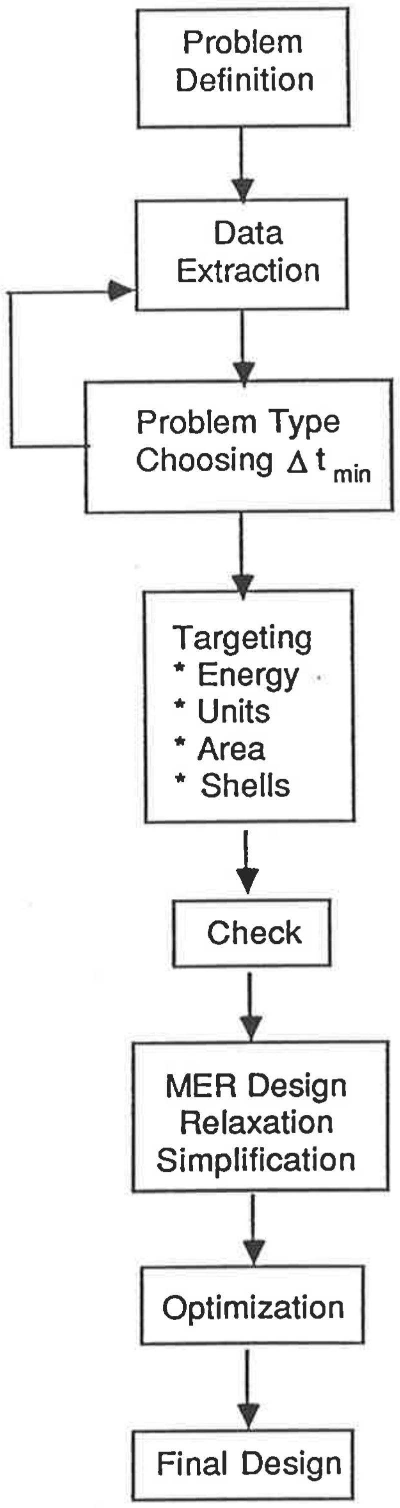


Figure 3.20: Modified overall design procedure

Chapter 4

Energy Relaxation in MER Heat Exchanger Networks

4.1 Introduction

To date most of the design methods proposed for the synthesis of heat exchanger networks, including the pinch design method, are based on a decomposition and evolutionary strategy [109]. An initial network is generated, based on heuristics or on broad thermodynamic principles. This initial network normally contains a number of units which is large compared to the theoretical minimum and which represents an excessive capital cost situation. Various heuristic methods are used to simplify the initial network by reducing the number of units.

In this chapter, a new technique is proposed for the systematic reduction of the initial (often large) number of units. The reduction in the number of units incurs an energy penalty. It is assumed that it is desirable to minimize utilities costs associated with a particular topology so the energy penalty incurred on removal of a unit should be minimized. The method developed will be demonstrated using the pinch design method only, however, it could be extended to the dual temperature approach method [25] used in HEXTRAN.

Given a value of minimum approach temperature, $\triangle t_{min}$, the pinch design method [91] has proved to be very efficient for synthesizing an initial network, featuring maximum energy recovery (MER). In this chapter, a new systematic method using mathematical programming techniques, namely mixed integer non-linear programming (MINLP), is proposed for the efficient reduction of the number of units in such networks. A loop and path identification tree algorithm (LAPIT) is presented to identify systematically the loops present in the network. Consideration of the loop-network interaction allows the determination of the most constrained unit (by approach temperature) in a loop. The loads of such units may not be increased without an overall energy penalty equivalent to that of the increased load. Hence these units are targeted for removal. The order of loop breaking is important as it also affects the resulting energy penalty. All the loops present in the MER network are investigated and a conservative estimate of the energy penalty associated with the removal of all the units is calculated. For a majority of units, the lower bound on energy penalty can be easily calculated by inspection. A 'best-first' search [129] is utilized for finding the optimal solution. Promising candidate units featuring the least energy penalty are considered for removal and the associated energy penalties are obtained. For the residual topology a NLP/LP is solved. The search space is considerably reduced by using the conservative estimator with the 'best-first' heuristic search. The procedure is illustrated by applying it to a typical problem.

4.2 Minimum Number of Units and Heat Load Loops

The capital cost of a network depends upon the number of units and the number of shells present in it as well as the associated pipe work. The goal of unit reduction concentrates the heat transfer area on fewer matches with less piping and foundation requirements and hence tends to minimize capital requirements for a given level of energy consumption. A detailed discussion on minimum number of units is given in chapter 2.

Linnhoff and Hindmarsh [91] suggested that, as the MER design is a combination of two independent subnetworks, equation 2.3 should be applied to both designs separately. The total for the whole problem "U_{minMER}", is the sum of the U_{min} for each subnetwork. Targeting for an MER design leads to counting the streams crossing the pinch twice and so,

$$U_{min} \leq U_{minMER} \tag{4.1}$$

However, as noted earlier, in equation 2.5, extra units are due to the presence of heat load loops in the network. Hence, the number of loops present in a MER network is,

$$L = U_{minMER} - U_{min} \tag{4.2}$$

The units present in each loop will be on either side of the pinch and so are "cross pinch loops".

Pinch problems have been designed which achieve both the U_{min} and utility targets [160]. These networks contain *exchangers* which cross the pinch and have *equal* C_p values for the hot and cold streams[1]. Stream splitting, bypassing, and mixing are used to achieve these designs. The total area of the network is relatively high and a large number of shells will be required for the match having the same C_p values. These designs seem to be more appropriate for problems having approximately parallel composite curves.

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[1] Heat exchangers with "equal C_p's " often have unusually large capital cost so the U_{min} designs may not be as desirable as usually indicated.

4.2.1 Loop Identification

To identify loops, Su [141,142] has proposed a definition of "level of loops". The "nth level loops" are the loops that involve n hot streams and n cold streams. By this definition, the first level loops are those loops that involve one hot stream and one cold stream, the second level loops involve two hot and two cold streams and so on. The highest loop level possible in a network is the smaller of either the number of hot streams or cold streams. For a stream to be in a loop, it must exchange heat in at least two units. This helps to locate the streams involved in forming a loop. The following loops can be identified in Figure 4.1 :

First level loop : (3,5)

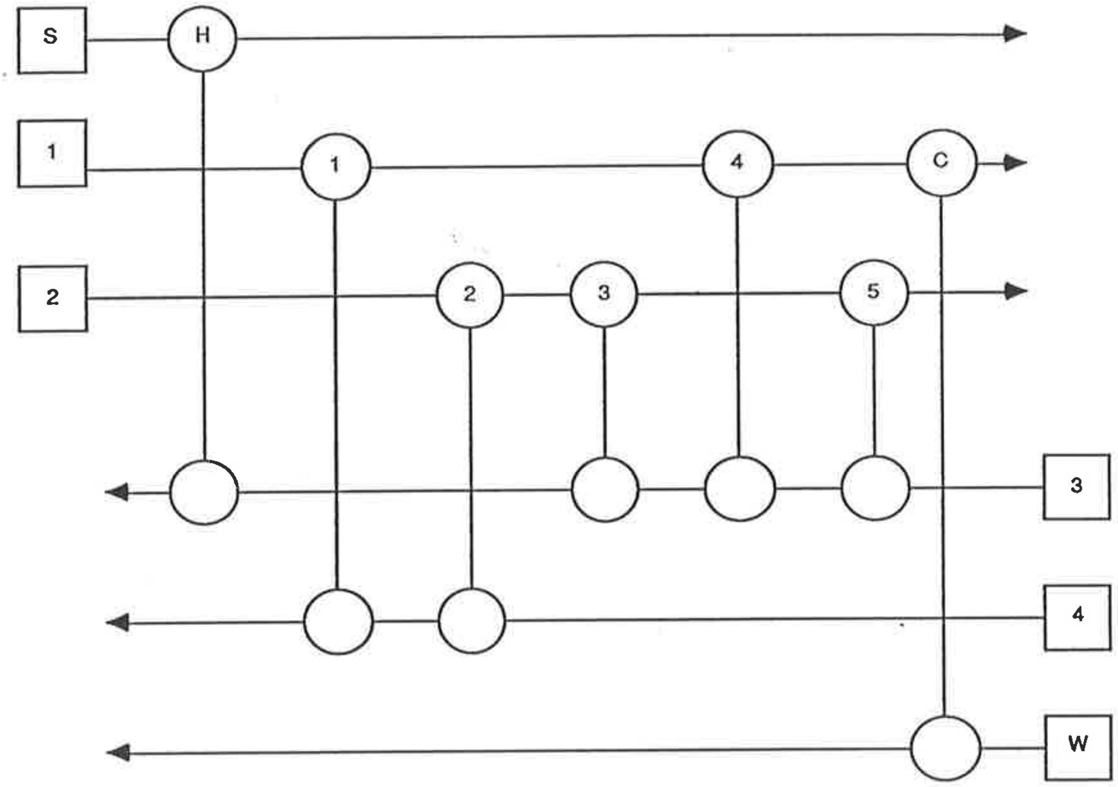
Second level loop : (1,2,3,4), (1,2,5,4)

The maximum number of loops, L_{max} present in a network is given by [27]

$$L_{max} = 2^L - 1 \tag{4.3}$$

These L_{max} loops will be combinations of the L independent loops and may have some duplicate loops. It is very difficult to identify visually all the loops present in complex networks. Any heat exchanger network can be represented as a graph. Gibbs [39] has proposed an algorithm for finding all the loops present in a graph. However, to apply this algorithm for heat exchanger networks, the grid diagram has to be converted into an Euler diagram [100]. The first step of the algorithm is to generate a spanning tree and then to find the fundamental loops associated with this spanning tree (see Appendix C for glossary). All the loops present in the network are found by successive stages, and by suppressing all the non-loops that arise at each stage before going to the next stage.

Su [141] has also developed a loop identification algorithm (LIA) for finding loops in a heat exchanger network. It is based on the flowsheet loop-finder algorithm



LOOPS (3,5), (1,2,3,4), (1,2,5,4)

Figure 4.1: Loop levels

proposed by Forder and Hutchison [34]. This algorithm is effective in finding loops in a network but requires a large number of steps.

As will be noted later, we are interested only in locating loops associated with certain units during the analysis. Hence, the above algorithms have to be modified so that it can be easily used, and all the loops associated with an unit can be found from the grid diagram.

LAPIT, **L**oop **A**nd **P**ath **I**dentification **T**ree, is a simple method for identifying loops present in a network associated with a particular unit. It is based on the method proposed by Paton [119].

The grid diagram can be represented in the form of a matrix. For the design shown in Figure 4.1 the "grid matrix" is shown below

Unit number	H	1	2	3	4	5	C
Hot stream	S	1	2	2	1	2	1
Cold stream	3	4	4	3	3	3	W

Units can be represented by an ordered triplet. The members of the triplet are the unit number, followed by the hot stream code and the cold stream code. Thus, unit 1 can be represented as (1,1,4). Table 4.1 shows all the units associated with each of the hot and cold streams.

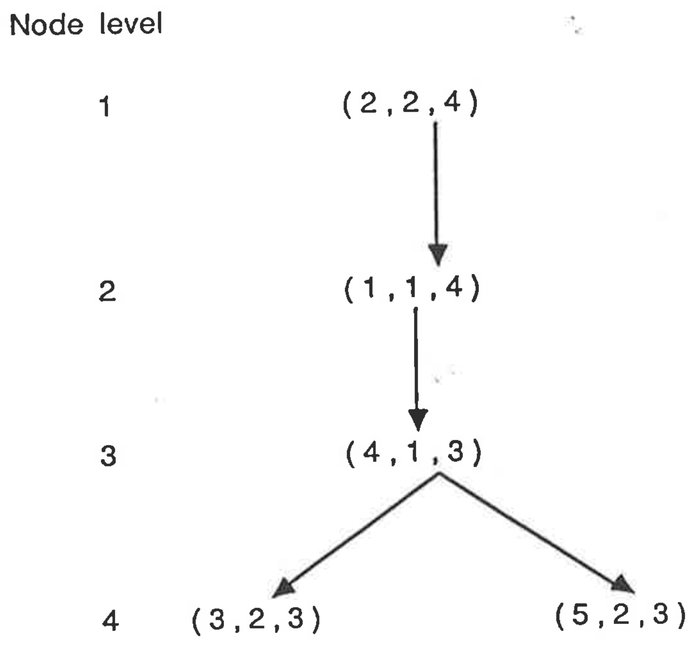
Those units which are not part of any loop are removed from the table e.g. (H,S,3) and (C,1,W) because S and W are only associated with one unit. With the help of this table the loop identification tree can be easily generated. Select a unit say, unit 2 (triplet (2,2,4)). The code for this unit will be placed on the first node level (root) of the tree. For this unit to be in a loop, the second level nodes should have units linked to its hot or cold streams. Choosing the cold stream 4, the linked unit found in the above table is (1,1,4). Unit 2 is not included again as it is the root. The tree is further branched to node level three. All the units linked to the hot stream of the

Table 4.1: Unit Code Table

Hot Streams		Cold Streams	
Stream Code	Unit Code	Stream Code	Unit Code
S	(H,S,3)	3	(H,S,3)
1	(1,1,4)		(3,2,3)
	(4,1,3)		(4,1,3)
	(C,1,W)		(5,2,3)
2	(2,2,4)	4	(1,1,4)
	(3,2,3)		(2,2,4)
	(5,2,3)	W	(C,1,W)

unit on node level two are found. Repetition of units on a branch is not allowed, but units may appear on more than one branch. Here, the third level node is (4,1,3). The fourth level nodes will consist of units linked to the cold streams of unit on the third level i.e. (3,2,3) and (5,2,3).

If only second level loops are required the branching of the tree can be stopped at the fourth node level, since an nth level loop will have 2n units. At each even node, all the vertices should be investigated to find if the unit representing the vertex is on the same hot stream as the root node. Such a vertex should not be further explored and is called a *fathomed* vertex. The other vertices are called *live* vertices. For higher level loops, the *live* vertices can be further branched in the same way, till the desired node level is reached. If the tree does not branch further, it indicates that the unit at the root does not have any higher level loops. This procedure may then be repeated for all the units in the network. The tree generated in the above example is shown below:-



To find the loop(s), simply find the units at the required level node which have the same hot stream as the root node (in this example stream 2). The loop can be traced by backward chaining (bottom to the top). In the above tree, the second level loops are (3,4,1,2) and (5,4,1,2). Here, both vertices on node level 4 are *fathomed.* Unit 2 cannot have any higher level loops. The advantage of this method is that once the tree is generated, all the loops associated with the unit on the first node level can be quickly identified; ie. the complexity is proportional to the level of the loop.

Advantage can also be taken of the property of the loops present in the network. As all the loops are normally across the pinch point, a set of loops associated with units either above or below the pinch point will be the set of all loops present in the network. This stops the generation of additional combinations and thus reduces the search space.

To compare the above method with Su's loop identification algorithm consider the example shown in a grid matrix below

Unit Number	1	2	3	4	5
Hot Stream	1	2	2	2	1
Cold Stream	2	2	1	2	1

LIA (as used by Su [141]) required 14 steps to identify all the loops associated with unit 1. LAPIT will require only 4 steps as the highest level of loops for this problem is two. Futhermore, LIA cannot identify paths whereas this may be done by LAPIT.

To identify paths for energy relaxation, the first node level in the tree will be a heater. The tree will stop branching when the unit on any node level is a cooler. This method can also be used to find paths between disturbances and control points in the study of operability of networks [93].

4.3 Procedures for Network Simplification

4.3.1 Use of Paths to Eliminate Units

If a unit is on a *path* between a heater and a cooler, it may be easily eliminated. The heat load of the unit removed is added to both the utility exchangers thus, incurring an energy penalty. The unit removed along a path has to be at an even position with respect to utility heaters and coolers. In Figure 4.1, units 1 and 3 can be removed along the path (H,3,2,1,C), but not unit 2 as redistribution of the heat load indicates that the heat load on the utility exchangers will decrease.

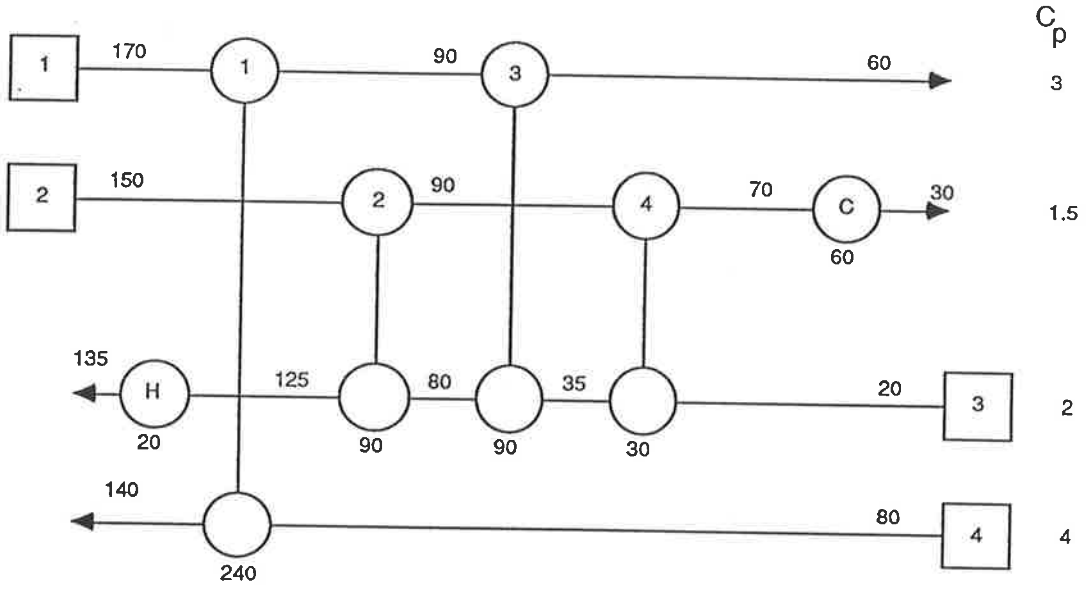
4.3.2 Loop Breaking

Loop breaking will often allow network simplification with a smaller increase in utility consumption. Loops can be broken by removal of a unit in a loop and redistribution of the load of the unit among the remaining units of the loop [91,100]. Breaking first level loops such as loop (3,5) of Figure 4.1 is achieved simply by adding the heat load of one unit to the other. When second and higher level loops such as loop (1,2,3,4) of Figure 4.1 are broken, the heat loads of some units will increase, while others will decrease. Thus, if the load of unit 1 in Figure 4.1 is X, elimination of this unit will cause the loads of unit 2 and unit 4 to increase by X and that of unit 3 to decrease by X. Following such loop breaking, restoration of the individual exchanger $\triangle t's$ to $\triangle t_{min}$ is achieved by increasing the utility consumption along a path (between a heater and a cooler).

The maximum heat load that can be transferred around a loop is decided by the highest load of the units present in the loop. But, if loops are broken by removing loads other than the minimum load, the possibility exists that the load of the remaining exchangers may become negative. (Su [141,142] avoids consideration of such an outcome). However, such a negative heat load may be changed to zero, either by moving an appropriate heat load around another loop containing this exchanger or by energy relaxation along a path. By using this combination of measures, loop breaking plus the removal of the negative load unit, two units are removed from the network. Two units are also sometimes removed in more conventional loop breaking procedures, as on occasions, restoring violations of $\triangle t_{min}$ can only be achieved by eliminating a second unit along a path. If loop breaking gives a negative heat load, it is also possible to seed the network with a dummy exchanger [42] and thus introduce a loop. This procedure will give a net reduction of only one unit.

These aspects of loop breaking will be illustrated by subsequent examples. Another important aspect of loop-breaking is the total number of U_{min} designs that have to be searched for finding the least energy penalty solution. Consider a seven stream problem [31]. A MER pinch design network for this problem has two first level loops, two second level loops and a third level loop. To find the U_{min} design featuring least energy penalty, by exhaustive search 192 networks would have to be investigated (see Appendix C). This number assumes that the network will not be seeded with dummy exchangers. Moreover, as more than one MER design can be developed, the number of designs to be investigated is even larger. Clearly, a systematic method is needed to identify which loops are to be broken and the units that should be removed, in order that a minimum energy penalty network can be achieved.

The systematic search method of Jones and Rippin [67] could be used to solve this problem. They demonstrated that the heat loads for MER designs satisfying the U_{min} target may be obtained as solutions to sets of linear (enthalpy balance) equations for the network. If there are no MER designs satisfying the U_{min} target, Jones and Rippin [67] showed that their procedure can find the minimum energy penalty for U_{min} designs by comparing the penalties of all feasible heat load distributions. However, the networks so obtained [67] frequently contain the same features as those discussed by Wood et al. [160] which can lead to large network areas and so may not be economically acceptable. Hence, the author considers that the evolutionary procedure presented here has an advantage in that the designer can control the development of the network and may retain or remove features such as stream splitting. In such network development it would be very helpful to know the energy penalty target for a specified number of units, however to date this is an unresolved problem.



LOOP (2,4)

Figure 4.2: MER design for example 4.1 [100]

4.3.3 Illustration of Energy Relaxation

A MER design given by Linnhoff and Hindmarsh [91] for a four stream problem (Table 4.2) is detailed in Figure 4.2. The minimum hot and cold utility requirements are 20 kW and 60 kW for a Δt_{min} value of 10 K. The pinch is located at the temperature of 90 °C for hot streams and 80 °C for the cold streams. This initial design can now be modified to reduce the number of units.

Table 4.2: Data for example 4.1 [100]

$\Delta t_{min} = 10$ K

Stream Number	C_p(kW/K)	T_s(°C)	T_t(°C)
1	3	170	60
2	1.5	150	30
3	2	20	135
4	4	80	140

For this network,

$$U_{minMER} = (5-1) + (4-1) = 7$$

The network shown in Figure 4.2 has six units. This is because there is subset equality for stream 2 and stream 3 above the pinch. Therefore, the overall target ignoring the pinch for this problem is

$$U_{min} = 6 - 1 = 5$$

and there is one loop, the first level loop (2,4). To break loops, many heuristics have been used [100,112,120,135,141,142]. An established heuristic is to remove the unit with the smallest heat load [91,100]. In appendix D a new heuristic is proposed for removing an exchanger in a loop with the least exergy efficiency. However, neither of these heuristics have any formal justification.

Figure 4.3 illustrates the network evolved for example 4.1, using the Linnhoff's heuristic rule and restoring Δt_{min} by increasing the utility requirement along the

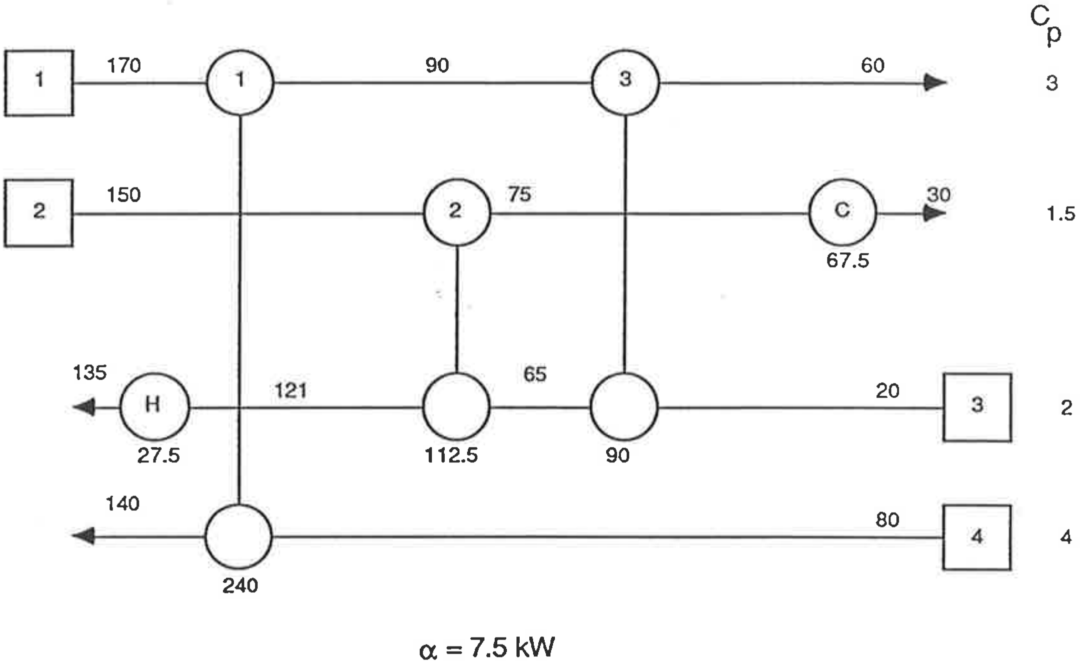


Figure 4.3: MNU design with α_{min} for example 4.1 [100]

path (H,2,C). In the above example, unit 4 with a heat load of 30 kW was removed. This led to an energy penalty (α) of 7.5kW [91]. Designs featuring the same energy consumption as well as the same topology are obtained by employing the exergy efficiency heuristic (see appendix D).

To generate an alternative problem, the data used above was altered by changing the starting temperature of stream 2 to 100°C. This revised data is given in Table 4.3. An MER design for this data with the same topology as that of Figure 4.2, is illustrated

Table 4.3: Data for example 4.2

$\Delta t_{min} = 10$ K

Stream Number	C_p(kW/K)	T_s(°C)	T_t(°C)
1	3	170	60
2	1.5	100	30
3	2	20	135
4	4	80	140

in Figure 4.4. Removal of the smallest heat load (unit 2) leads to Figure 4.5 which has an energy penalty of 15 kW. However, removal of unit 4 gives the design in Figure 4.6 with an energy penalty of only 7.5kW. So strict adherence to Linnhoff's heuristic rule has led to an unnecessary energy penalty. The heuristic of removing the least exergy efficiency indicated that unit 4 should be removed.

The above illustration had a single first level loop. Consider another problem tabulated in Table 4.4. An MER design for the problem is illustrated in Figure 4.7. There are three loops - (1,5), (1,2,3,4) and (2,3,4,5). Su [141,142] has recommended that lower level loops should be given first preference. Table 4.5 details the minimum energy penalty on breaking the above loops. Employing the Su's heuristic leads to a larger energy penalty. Futhermore, the energy penalty resulting on removal of a unit depends upon the associated loop that is broken. Hence, all the loops containing the unit under consideration should be investigated, to determine the minimum energy penalty.

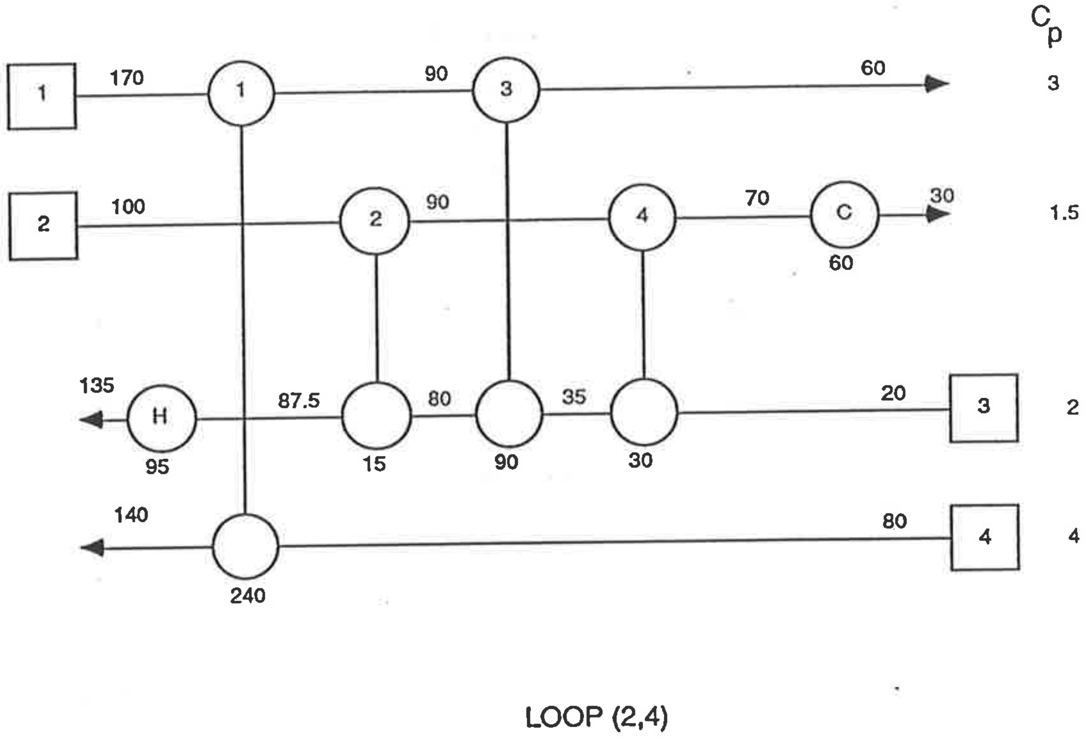


Figure 4.4: MER design for example 4.2

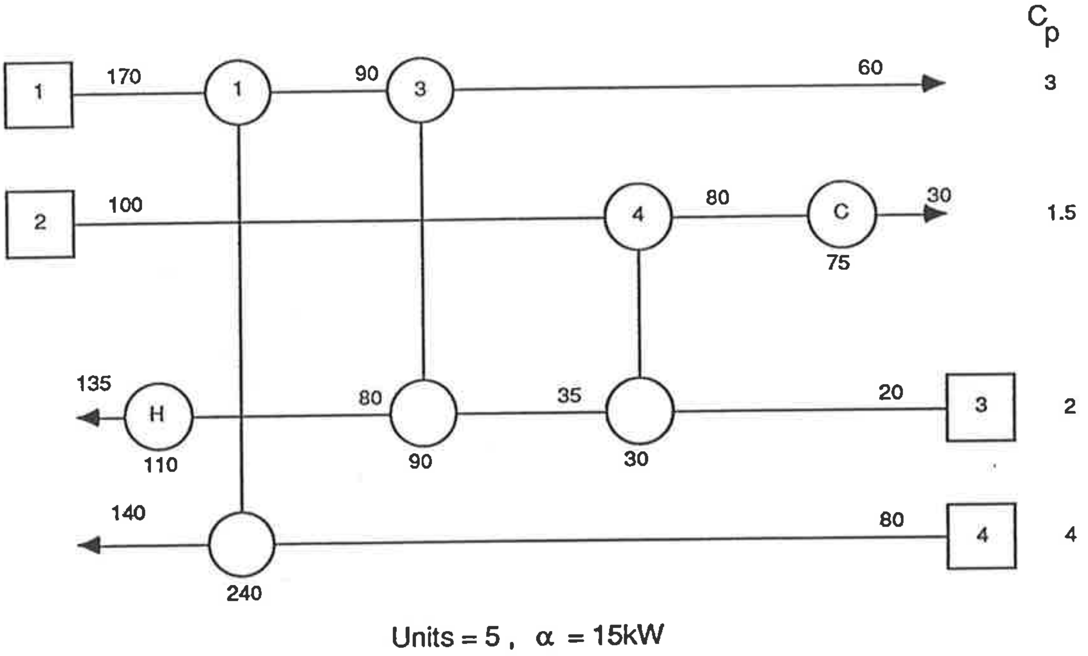
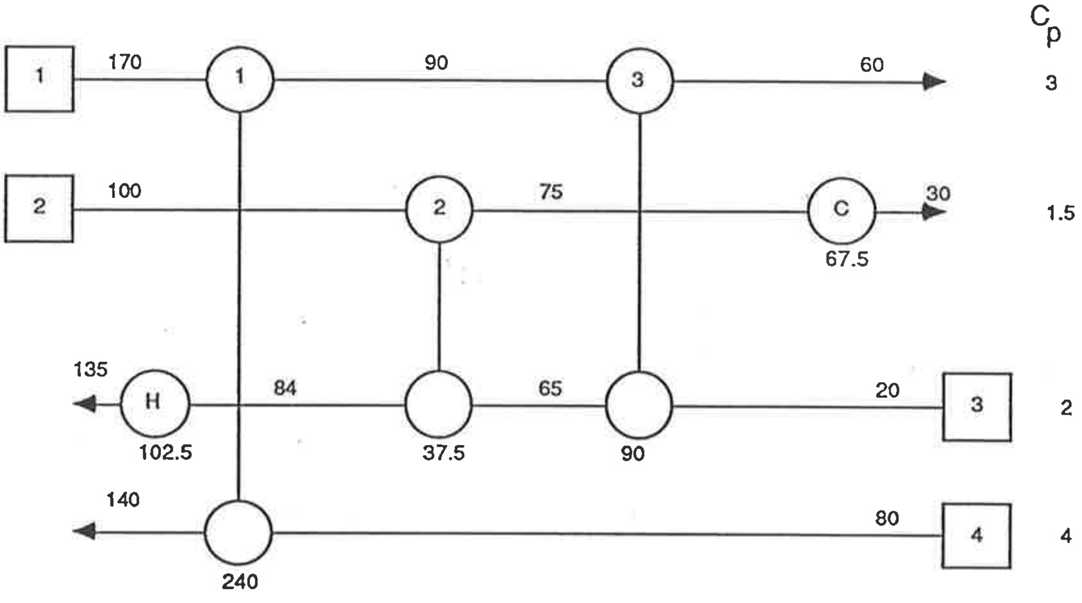


Figure 4.5: MNU design obtained on removing unit 2 from the design illustrated in Figure 4.4



Units = 5, α = 7.5kW

Figure 4.6: MNU design obtained on removing unit 4 from the design illustrated in Figure 4.4

Table 4.4: Data for example 4.3 [91]

$\Delta t_{min} = 10$ K

Stream Number	C_p(kW/K)	T_s(°C)	T_t(°C)
1	2	150	60
2	8	90	60
3	2.5	20	125
4	3	25	100

Table 4.5: Minimum energy penalties for example 4.3

Loop	Unit Removed	α kW
(1,5)	5	20
(2,3,4,5)	5	6.7
(1,2,3,4)	1	30

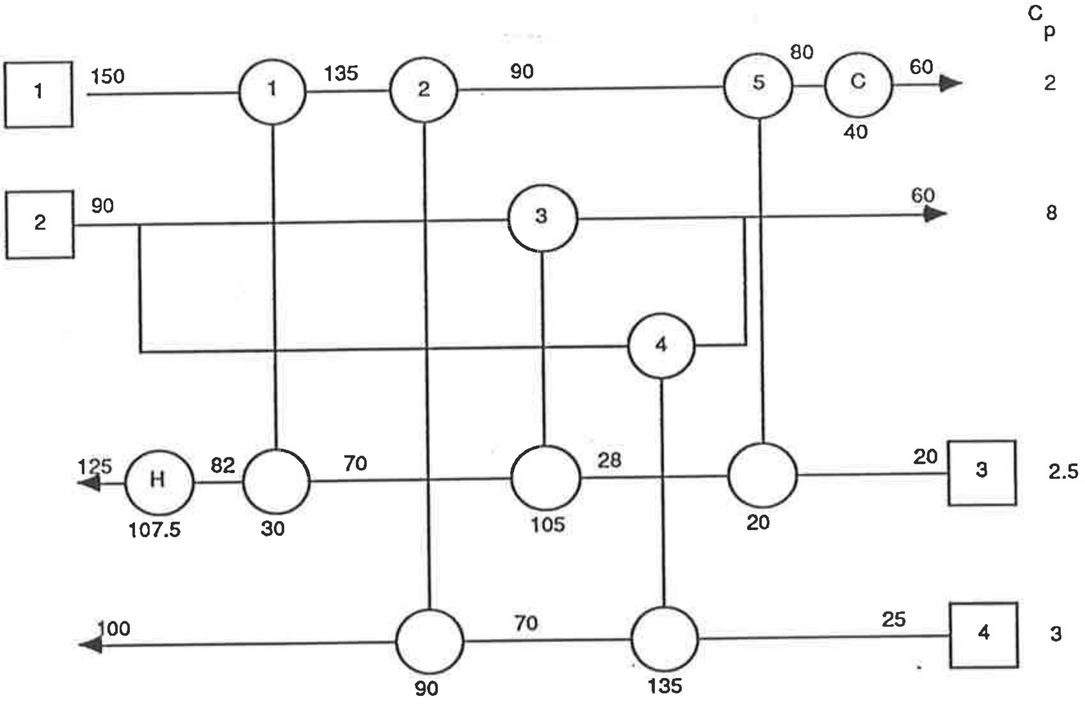


Figure 4.7: An MER design 1 for example 4.3 [91]

From the above illustrations, two conclusions can be drawn:

a) Removing the smallest unit in a loop does not guarantee a minimum energy penalty.

b) Energy penalty is dependent on the unit and the associated loop broken.

Due to the above reasons, all the units in a loop will have to be investigated for the consequent energy penalty. Furthermore, all the possible loops along which the unit can be removed also have to be investigated. The solution of a mixed integer non-linear program, as discussed next, will indicate which unit/units to remove and the subsequent minimum energy penalty.

4.4 MINLP Formulation

The information available to derive the formulation comes from the MER network that is to be evolved. It is developed on the same lines as the NLP formulation of MAGNETS [29]. Information regarding the following items can be obtained from the MER network[2]:

- **Stream Data:**

  Let H be the set of all the hot streams and C be the set of all the cold streams. For every hot stream (process and utility), $i \in H$ and $j \in C$, the heat capacity flow rates C_{p_i} and C_{p_j} are specified. The starting and target temperatures of each hot and cold stream will be denoted by t_i^s, t_i^t, t_j^s and t_j^t respectively. The enthalpy of the hot and cold streams shall be denoted by Q_i and Q_j respectively. S and W are the set of hot and cold utilities. A temperature drop/rise of 1 K is assumed for any phase changes taking place. The heat capacity flow rate of the stream undergoing a phase change will then be equal to the corresponding latent heat of phase change.

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[2] The nomenclature used here is limited to this section only

- **Matches:**

  The MER design details the information about the stream matches. A stream match is a binary variable y_{ijk}. This variable represents the k^{th} exchanger which matches the hot stream i and the cold stream j. The value of y_{ijk} is 1 if such an exchanger exists, else it is zero. The heat load of such a match is denoted by Q_{ijk}.

The split stream topology of the MER network can be characterised by the following index sets. All the hot and cold streams will be denoted by a common index q,

$$HC = H \cup C = \{q\}$$

Let the index set $(X_q = \{l\})$ denote the set of l streams associated with each stream q. The heat capacity of flow rates and the temperatures of these l streams are C^q_{pl} and t^q_l.

The splitters and the mixers associated with the stream splits shall be denoted by the index set $S_q = \{s\}$ and $M_q = \{m\}$ respectively. The splitter $s^\circ \in S_q$ will stand for the initial splitting point in the stream structure q, while $m^\circ \in M_q$ will stand for the final mixing point in that stream. The following sets of splitters and mixers with internal input and output streams are also defined:

$$S^{IN}_q(s) = \{l/l \in X_q \text{ is an inlet to splitter } s\}$$

$$S^{OUT}_q(s) = \{l/l \in X_q \text{ is an outlet to splitter } s\}$$

$$s \in S_q$$

$$M^{IN}_q(m) = \{l/l \in X_q \text{ is an inlet to mixer } m\}$$

$$M^{OUT}_q(m) = \{l/l \in X_q \text{ is an outlet to mixer } m\}$$

$$m \in M_q$$

The inlet and the outlet streams to each exchanger is given by:

$$E_{ijk}^{HIN} = \{n/n \in X_i \text{ is the inlet of the hot stream } i \text{ to unit } k\}$$

$$E_{ijk}^{HOUT} = \{p/p \in X_i \text{ is the outlet of the hot stream } i \text{ to unit } k\}$$

$$E_{ijk}^{CIN} = \{u/u \in X_j \text{ is the inlet of the cold stream } j \text{ to unit } k\}$$

$$E_{ijk}^{COUT} = \{r/r \in X_j \text{ is the outlet of the cold stream } j \text{ to unit } k\}$$

The MINLP formulation using the above index sets is:

Objective:

$$min \sum_{i \in S} \sum_{j} \sum_{k} Q_{ijk} + \sum_{i} \sum_{j \in W} \sum_{k} Q_{ijk}$$

Subject to:

Stream Heat Balance:

$$\sum_{j} \sum_{k} y_{ijk} Q_{ijk} = Q_i \qquad i \in H$$

$$\sum_{i} \sum_{k} y_{ijk} Q_{ijk} = Q_j \qquad j \in C$$

Exchanger Heat Balances:

$$C_{p_l}^i (t_n^i - t_p^i) = Q_{ijk} \qquad n \in E_{ijk}^{HIN},\ p \in E_{ijk}^{HOUT}$$

$$C_{p_l}^j (t_r^j - t_u^j) = Q_{ijk} \qquad u \in E_{ijk}^{CIN},\ r \in E_{ijk}^{COUT}$$

Minimum Approach Temperature Constraint:

$$t_n^i - t_r^j \geq \Delta t_{min} \qquad n \in E_{ijk}^{HIN},\ r \in E_{ijk}^{COUT}$$

$$t_p^i - t_u^j \geq \Delta t_{min} \qquad p \in E_{ijk}^{HOUT},\ u \in E_{ijk}^{CIN}$$

Mass Balance on Splitters:

$$\sum_{l \in S_q^{IN}(s)} C_{p_l}^q = \sum_{l \in S_q^{OUT}(s)} C_{p_l}^q \qquad s \in S_q,\ q \in HC$$

Mass Balance on Mixer:

$$\sum_{l \in M_q^{IN}(m)} C_{p_l}^q = \sum_{l \in M_q^{OUT}(m)} C_{p_l}^q \qquad m \in M_q,\ q \in HC$$

Heat Balance on Mixer:

$$\sum_{l \in M_q^{IN}(m)} C_{p_l}^q t_l^q = \sum_{l \in M_q^{OUT}(m)} C_{p_l}^q t_l^q \qquad s \in S_q,\ q \in HC$$

Specification for inlet mass heat capacity flowrates:

$$C_{p_l}^q = C_{p_q} \qquad l \in S_k^{IN}(s^o),\ q \in HC$$

where $C_{p_q} = \{C_{p_i},\ i \in H,\ C_{p_j},\ j \in C\}$

Specification for inlet and outlet temperatures:

$$t_l^i = t_i^s$$

if t_l^i is the inlet temperature of the first exchanger on the hot stream i.

$$t_l^i = t_i^t$$

if t_l^i is the outlet temperature from the last exchanger on the hot stream i or is the outlet temperature from the last mixer on stream i.

$$t_l^j = t_j^s$$

if t_l^j is the inlet temperature of the first exchanger on the cold stream j.

$$t_l^j = t_j^t$$

if t_l^j is the outlet temperature from the last exchanger on the cold stream j or is the outlet temperature from the last mixer on stream j.

Equality constraints on the splits:

$$t_l^q = t_p^q \qquad l \in S_q^{IN}(s),\ p \in S_q^{OUT},\ s \in S_q,\ q \in HC$$

Non-negativity constraints:

$$C_{p_l}^q \geq 0 \qquad l \in X_q \text{ and } q \in HC$$

Number of units constraints:

$$U_{min} \leq \sum_i \sum_j \sum_k y_{ijk} \leq U_{min_{MER}}$$

where $U_{min_{MER}}$ is the upper limit on the number of units required in the evolved design.

As noted previously, sometimes removal of a unit and redistribution of the heat load may cause a negative heat load on some of the remaining heat exchanger units. To avoid this, the network is seeded with a dummy *utility* exchanger, introducing a loop to remove the negative heat loads [42]. For solving the proposed MINLP, and to account for the above mentioned cases, dummy units should be introduced in the MER topology.

The solution to the proposed MINLP model is not a trivial task. The methods reported in the literature, recommend to convert the MINLP formulation to a NLP, by selecting some combinations of the binary variables. The same philosophy is followed here. A 'best-first' strategy is used. By studying the loop-network interactions, the most constrained units can be identified. This interaction analysis helps in identifying the candidate units for removal. A simple formula is also developed to target for the minimum energy penalty that would result on removal of some candidate units in a given loop. This estimator, for the lower bound on the energy penalty is used to carry out the 'best-first' search. Employing this approach, it should be noted that split stream designs would involve the solution of a NLP, and unsplit designs can be transformed into an LP. Existing algorithms can then be used to find the solutions to the reduced problem. At times, it may be possible to obtain the optimal solution by hand calculations.

4.5 Loop - Network Interaction

In the existing procedure for loop breaking, the loop is isolated from the network, implying that the loop can be treated as a separate entity. This assumes that the loop does not interact with the network which clearly is an oversimplification. Thus it is necessary to investigate loop-network interactions.

The objective of loop-network interaction analysis is to discover certain critical exchangers which restrict the process of energy efficient loop breaking. These are

Type A:

A unit that is located on a stream entering the network and has a temperature difference equal to $\triangle t_{min}$. Such units are often found immediately adjacent to the pinch and their heat load can only be decreased.

Type B:

This unit is necessary in the network for one of the streams in this match to achieve its target temperature. Therefore the heat load of a unit of Type B may either be increased or decreased but the unit cannot be eliminated.

Type C:

On loop breaking, the heat load of the unit removed is added to some of the remaining units from the loop. However, units of Type C cannot absorb this load fully and the surplus must be removed along a path. The magnitude of this surplus is the lower bound for the energy penalty following such loop breaking.

These three types of exchangers are illustrated in Figure 4.8.

Some of the constraints implied in this classification of exchangers have been successfully used previously to reduce the search for feasible heat exchanger networks [33]. However, the importance of units of Type A does not appear to have been noted previously. It should also be noted that, this analysis differs from the calculation of the freedom of exchangers [96]. Following such analysis, all exchangers at the pinch would have zero freedom and therefore could only decrease in load. Whereas here, a pinch exchanger may increase in load, if the Δt_{min} violation may subsequently be restored by energy relaxation along a path involving this exchanger.

If there is a unit in a loop of Type A, it will determine which loads of the units in a loop may increase (be positive ('+')) or decrease (be negative ('-')). For the data of example 4.4, given in Table 4.6, an MER network is presented in Figure 4.9. Focussing on the second level loop (1,2,4,3), unit 2 is of Type A and therefore is assigned a '-' sign. Hence, the signs of the other units in this loop are readily found by enthalpy balance and are shown on the units in Figure 4.9.

The above analysis is called **LO**op **N**etwork **I**nteraction and load **T**ransfer **A**nalysis

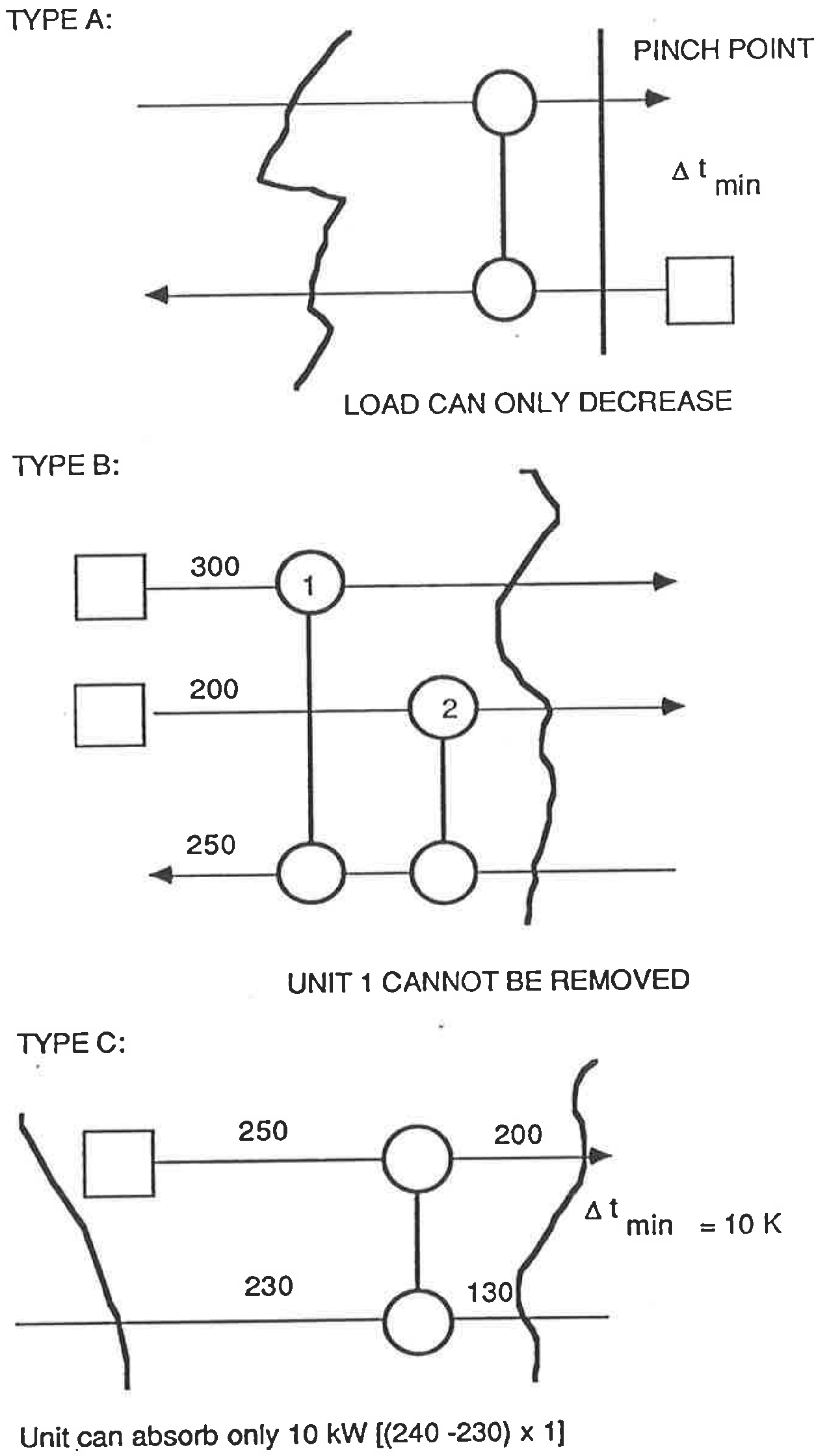


Figure 4.8: Loop-network interaction

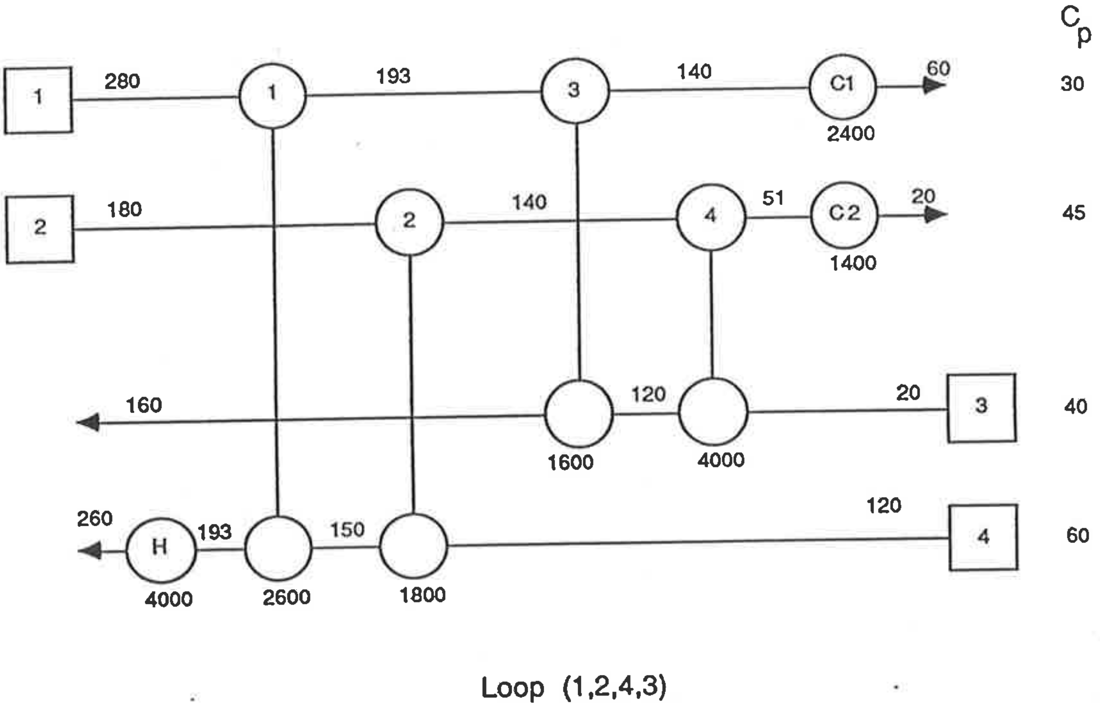


Figure 4.9: MER network for example 4.3

Table 4.6: Data for example 4.4

$\Delta t_{min} = 10$ K

Stream Number	C_p(kW/K)	T_s(°C)	T_t(°C)
1	30	280	60
2	45	180	20
3	40	20	160
4	60	120	260

(LONITA) and locates the exchanger to be removed on breaking a loop as one of those with a '-' sign. This avoids removal of the other units which may cause large energy penalties. Furthermore, the search space for targeting the energy penalty has been reduced to half. An underestimate for the energy penalty on removal of a '+' sign exchanger is equal to the smallest heat load of a '+' sign unit present in the loop.

Identification of Type A units also explains why the elimination of unit 2 of load 15kW, from the network of Figure 4.4, leads to an energy penalty of the same magnitude. Unit 1 is of Type A. Because of the subset equality in this match above pinch, the temperature of stream 1 entering unit 3 is fixed at the pinch temperature. Thus, the load on stream 3 below the pinch, and hence that of unit 4 cannot be increased. Therefore unit 4 is of Type C. Adding the load of unit 2 to unit 4 simply results in an energy penalty equal to the load of unit 2. This same reasoning also explains why unit 4 should also be eliminated from the design of Figure 4.2.

4.6 Energy Penalty Targeting

To implement the 'best-first' search strategy for solving the MINLP, a heuristic function estimating the lower bound on the minimum energy penalty is required when an unit is removed. LONITA indicates the units in a loop whose heat load can be decreased. These are the units with '-' sign. Δt_{min} will not be violated across these exchanger units as the heat load of these exchangers decrease. The heat load of the exchangers with '+' sign will increase, consequently a Δt_{min} violation might occur across these exchangers. Futhermore, as the loop interacts with the network, other units not in the loop, may also violate the Δt_{min} constraint. It is very difficult to identify *a priori* such exchanger units. Hence, if we predict the minimum increase in energy consumption needed to restore the Δt_{min} across the '+' sign units, it will represent a lower bound on the actual energy penalty.

The energy penalty functions will be illustrated by breaking the second-level loop in the Figure 4.10. Application of LONITA indicates that units 3 and 4 are the likely candidates for removal. Let $Q_3 > Q_4$. The network, on redistribution of the heat load in the loop, on removal of unit 4 is shown in Figure 4.11. It can be easily observed that the temperatures of the streams entering and leaving the loop will not change. Only the intermediate temperatures within the loop will increase or decrease. Hence, the Δt_{min} violations across any unit will occur at the positions detailed in the Figure 4.11. In this case, the violation of Δt_{min} will be on the cold end of unit 2 and the hot end of unit 5. The minimum energy penalty to restore the approach temperatures across these units will be:

$$P_2 = Q_3 - Q_4 + C_{p5}\,(T_{15} + \Delta t_{min} - T_5)$$

$$P_5 = Q_3 - Q_4 + C_{p3}\,(T_9 + \Delta t_{min} - T_6)$$

$$EP = \max(P_2, P_5)$$

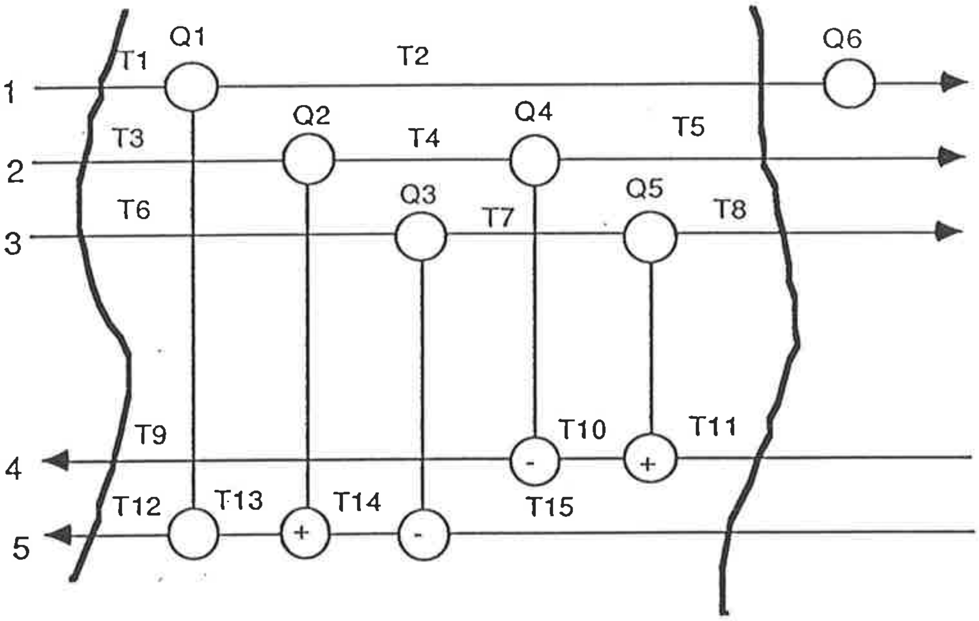


Figure 4.10: Loop (2,4,5,3)

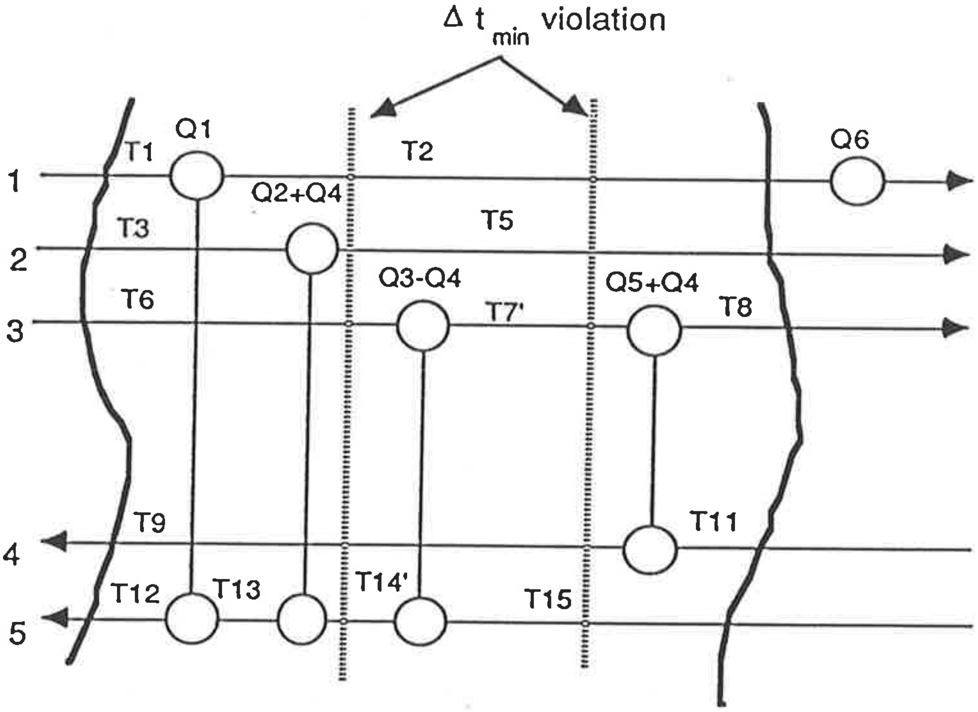


Figure 4.11: Network with unit 4 removed

At times, a unit in a loop that is broken, may be on a path. It may be possible to increase the heat load on such units and thus decrease the total energy penalty. This change in the energy consumption must be deducted from EP for evaluating the lower bound on the consequent energy penalty, $\alpha_{\text{lower bound}}$.

Employing such a simple calculation, a lower bound on the energy penalty can be easily evaluated. Relations of this type cannot be generalized and will be dependent on the loop that is broken. However, they can be easily calculated by the designer.

The network, on removal of unit 3 is illustrated in Figure 4.12. As $Q_3 > Q_4$, unit 4 will have a negative heat load. If unit 4 is at an even position with respect to the utility units, it can be removed along a path. Another option is to break a different loop having unit 4. In the present case, neither of these possibilities exist. The network is seeded with a dummy cooler, unit 7. This introduces a new loop (6,1,2,4,5,7). In this loop, unit 4 has a '+' sign (as it has a negative heat load) and has to be removed from the loop. Assigning the signs to the units constituting this loop, unit 6 has a '-' sign, indicating that its load should be decreased. Unit 4 can only be removed if the heat load of the units having '-' sign is greater than or equal to absolute value of $(Q_4 - Q_3)$. Assuming this fact is true, the new topology on redistribution of the heat loads is illustrated in Figure 4.13. The changes in the topology that have taken place are quite complex. The energy penalty as a result of these changes cannot be predicted easily. Hence, it is assumed that such units, if removed, will have no energy penalty. This a very conservative assumption and implies that during the search, the actual energy consumption on removal of such units from the network should be evaluated first.

The C_p value of split streams will be assumed to be the same as the unsplit stream when evaluating the penalty function. The lower bound on the energy penalty on removal of a unit with '+' sign in a loop, will be equal to the minimum heat load of all the unit having '+' sign. The evaluation of energy penalties will be illustrated by an example.

Consider the network illustrated in Figure 4.14. This network has three independent

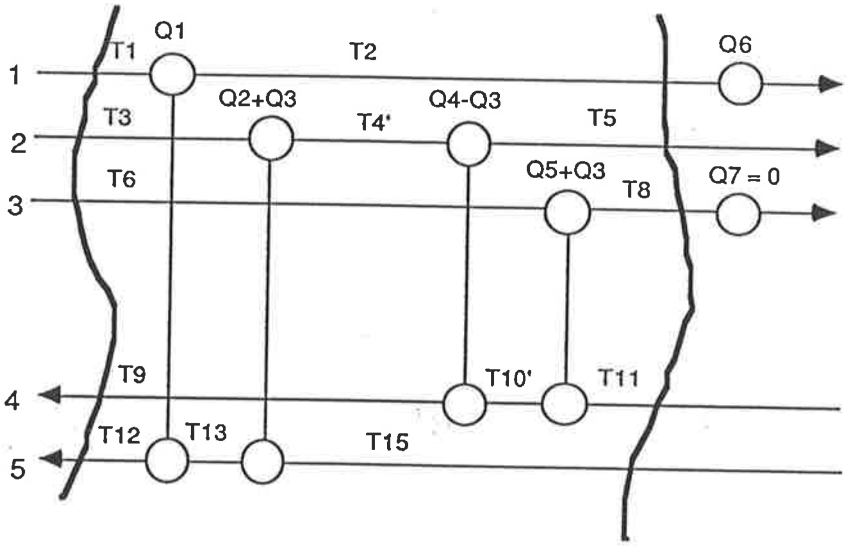


Figure 4.12: Network with unit 3 removed and seeded with unit 7

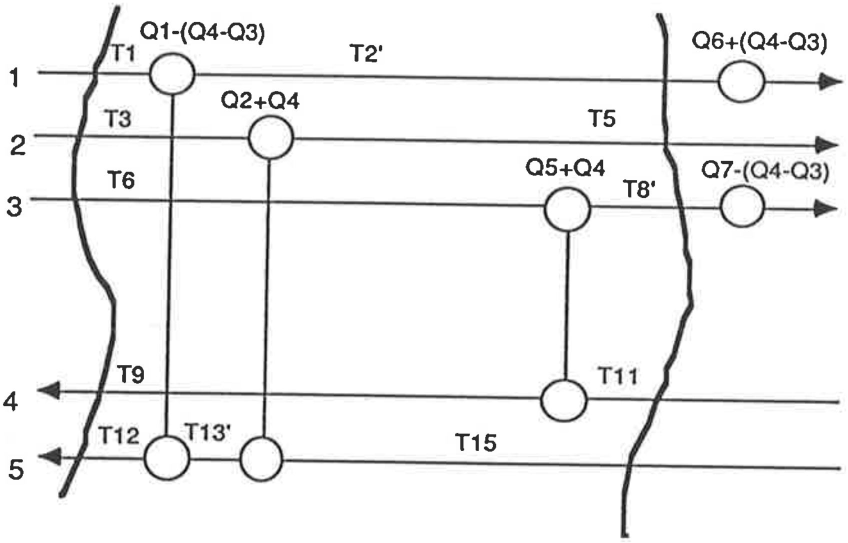


Figure 4.13: Evolution of the seeded network

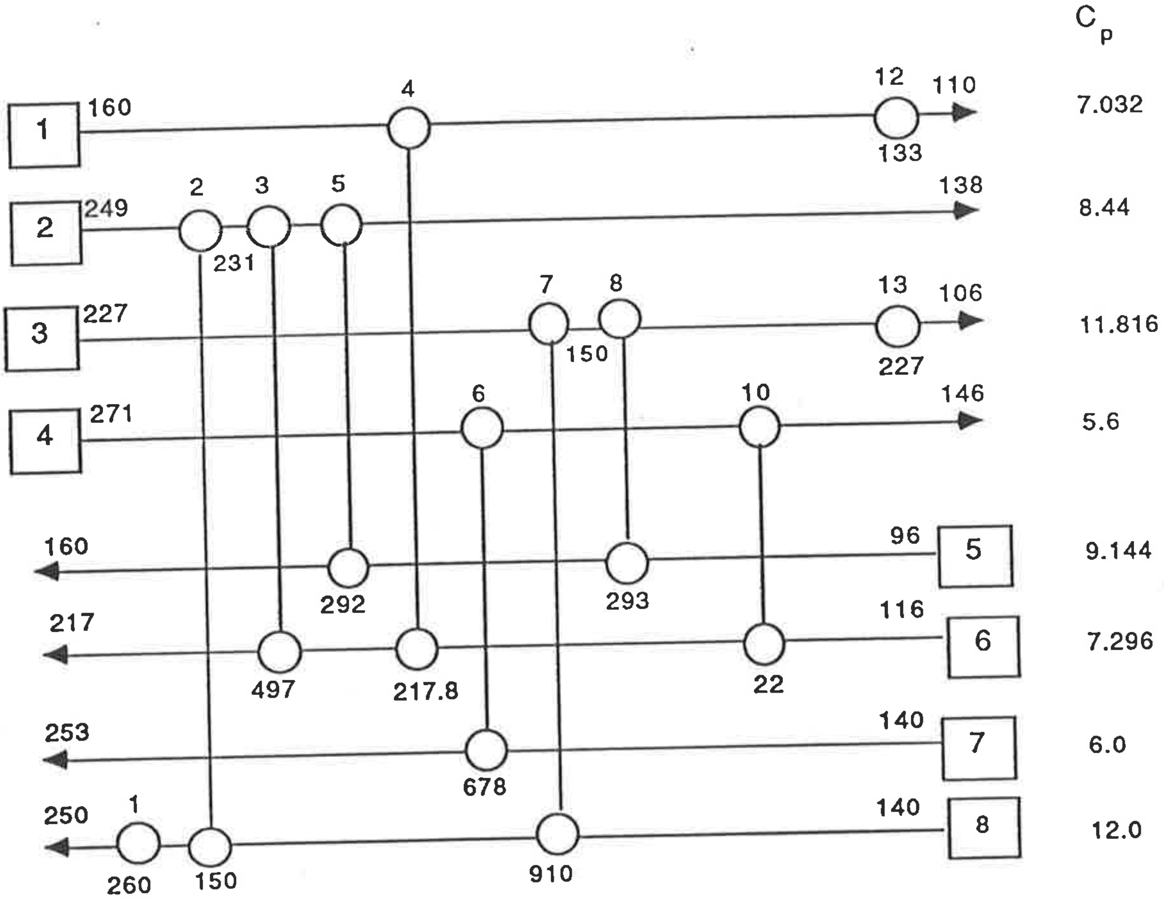


Figure 4.14: Network to illustrate the energy penalty calculations

loops :- (2,7,8,5), (2,7,13,12,4,3) and (3,4,12,13,8,5). Application of LONITA to loop (2,7,8,5) results in a (+,-,+,-) situation. This implies that if units 2 and 8 are removed then the energy penalty would be 150 kW and 293 kW respectively. As unit 7 has the largest heat load in the loop (2,7,8,5) it is very difficult to predict the energy penalty on removal of this unit and so is assumed to be zero. The energy penalty on removal of unit 5, P_5 is

$$P_5 = max(P_2, P_8)$$

The value of P_8 is zero as it can absorb all the heat load of unit 5.

$$P_2 = 292 - (8.44 \times (231 - 227)) = 258.24kW$$

Hence, the energy penalty on removing unit 5 would be 258.24 kW. However, stream 3 will be cooled to 174.69°C in unit 7 on redistribution of the heat load of unit 5. Since unit 7 is on a path it can absorb some extra heat load given by

$$P_7 = 11.816 \times (174.69 - 170) = 55.512kW$$

So the actual energy penalty on removal of unit 5 will be 202 kW (258.24 - 55.512).

4.7 Best-First Search Procedure

Two important observations have led to the selection of this strategy for solving the MINLP model. First, the number of units to be removed is known in advance. This fixes the depth of the search tree. Second, lower bounds on the energy penalty can be evaluated for a large number of the possible units that can be removed. Futhermore, the energy penalty always increases with the depth of the tree.

Best-first search is a very popular method for problem solving in Artificial Intelligence systems [129]. It is a way of combining the advantages of both depth-first and breadth-first search into a single method. At each step of the 'best-first' search process, we select the most promising of the nodes we have generated so far. The process starts by evaluating the heuristic estimator or the actual value for each of the possible units to be removed. We then expand the node which has the predicted least energy penalty to generate its successors. If we reach the U_{min} target we can quit. If not, all those new nodes are added to the set of nodes generated so far. Again the most promising node is selected and the process continues. Usually what happens is that a bit of depth-first searching occurs as the most promising branch is explored. But eventually, if a solution is not found, that branch will start to look less promising than one of the top-level branches that had been ignored. At that point backtracking occurs and the now more promising but previously ignored branch is explored. However, the old branch is not forgotten, its last node remains in the set of generated but unexpanded nodes and the search can return to it whenever the predicted performance for all the other nodes evaluates to an expected worse value. When this occurs expansion of the previously abandoned node is restarted.

Consider a hypothetical example to illustrate the above procedure. Figure 4.15 shows the beginning of the 'best-first' search. Initially, there is only one node, the MER design, so it will be expanded. Doing so generates the possibility of removal of three units. The estimates of the energy penalties is calculated for each of these three new nodes. Since node D is the most promising, it is expanded next, producing two new nodes, E and F. The heuristic function is now applied to them. At this stage, another path, that going through node B, looks more promising, so it is pursued, generating nodes G and H. But again, when these new nodes are evaluated they look less promising than another path, so attention is returned to the path through D to E. E is then expanded, yielding node J. At this level three units are removed. Design J is the solution to the MINLP, as it has the least energy penalty amongst all the designs investigated. Design E is the solution with two units removed. The above procedure may repeatedly evaluate the same designs. For example, a design can be evolved by removing two units. The energy penalty associated with this design is independent of the evolution path. A trail list of the designs already evaluated has to be kept to avoid such repetition.

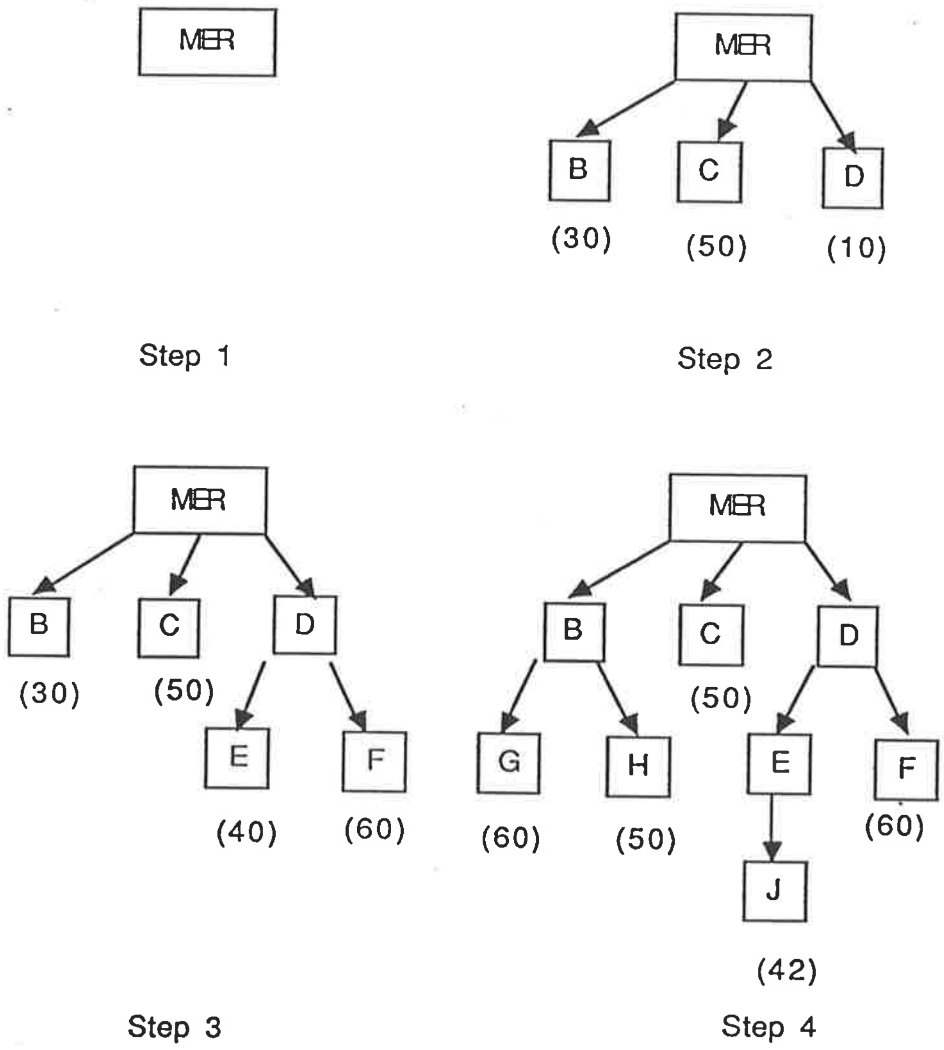


Figure 4.15: 'Best-first' search

Example 4.5

Table 4.7 details the data for an eight stream problem. Figure 4.16 illustrates a MER design for this data assuming a $\triangle t_{min} = 10$ K. This MER design has scope for removing four units. The total number of loops in this design is eleven. There are two first level loops, a second level loop, and rest being third level loops. As the objective is to achieve the minimum number of units with minimum energy penalty, the network is seeded with dummy exchanger units, 14,15,16,17,18. The total number of U_{min} designs that can be derived from the above network (after seeding with the dummy exchangers) is 4185 (see Kirchhoff's theorem outlined in appendix C). LONITA indicates that units 2,4,5,7,8,9,11 are the likely candidates for removal. The energy penalty targets for the removal of these units are reported in brackets in Figure 4.17. As estimates of the lower bound for the energy penalties incurred on removal of units 7 and 8 cannot be calculated, they are conservatively assumed to be zero. These two nodes are evaluated first. The objective is to find the actual energy penalties, by solving an LP derived from the original MINLP. Removal of unit 11 by breaking the loop (4,11) has the minimum energy penalty target, hence this node is expanded and the same analysis is carried out again on the resulting network. Now removal of unit 9 from the MER design looks the next most promising step because it has the lowest target energy penalty. The search is continued as outlined in the previous section until a U_{min} design is obtained. Certain nodes are *fathomed* as they then lead to previously evolved design topologies and further expansion would be unprofitable. A U_{min} design with the least energy penalty is illustrated in Figure 4.18. A total of 68 nodes where investigated as illustrated in the search tree of Figure 4.17 and of these only 28 required expansion (A systematic non-heuristic search would have had to investigate a minimum of 4185 topologies).

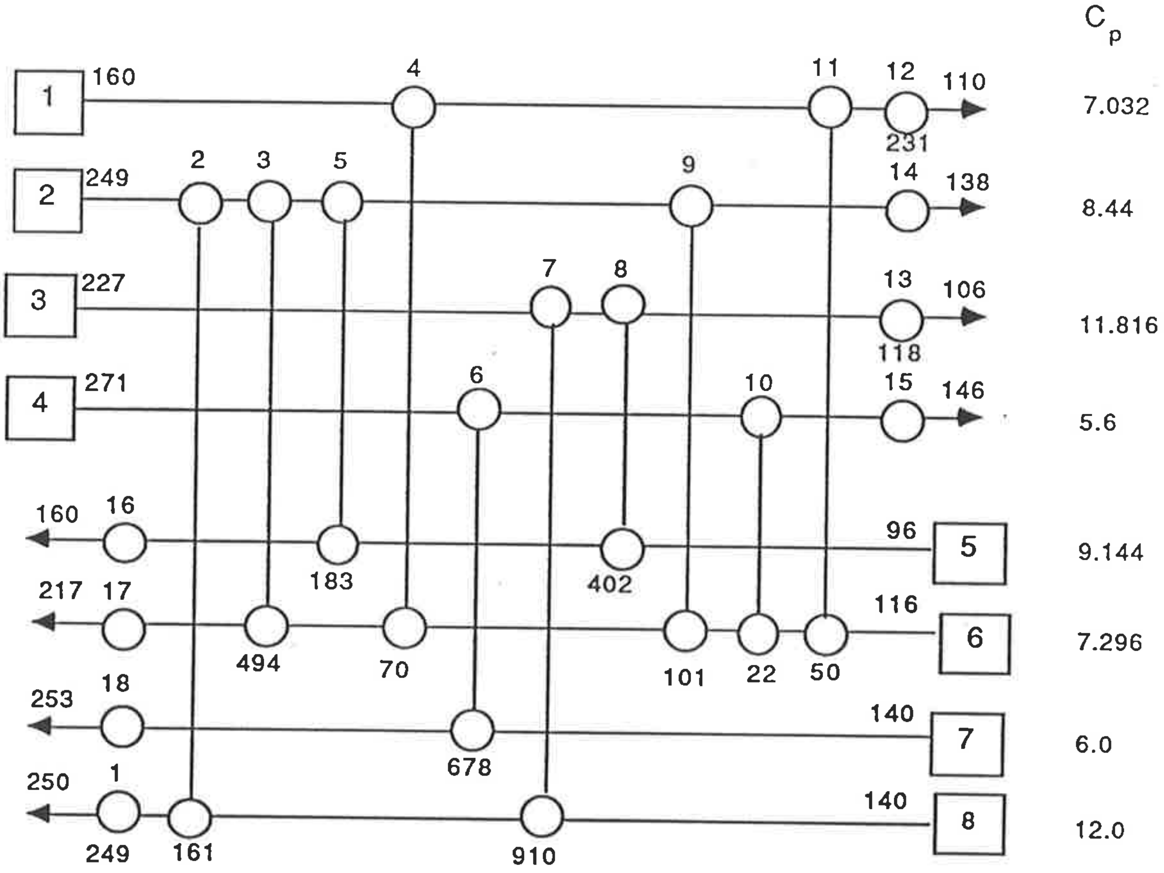
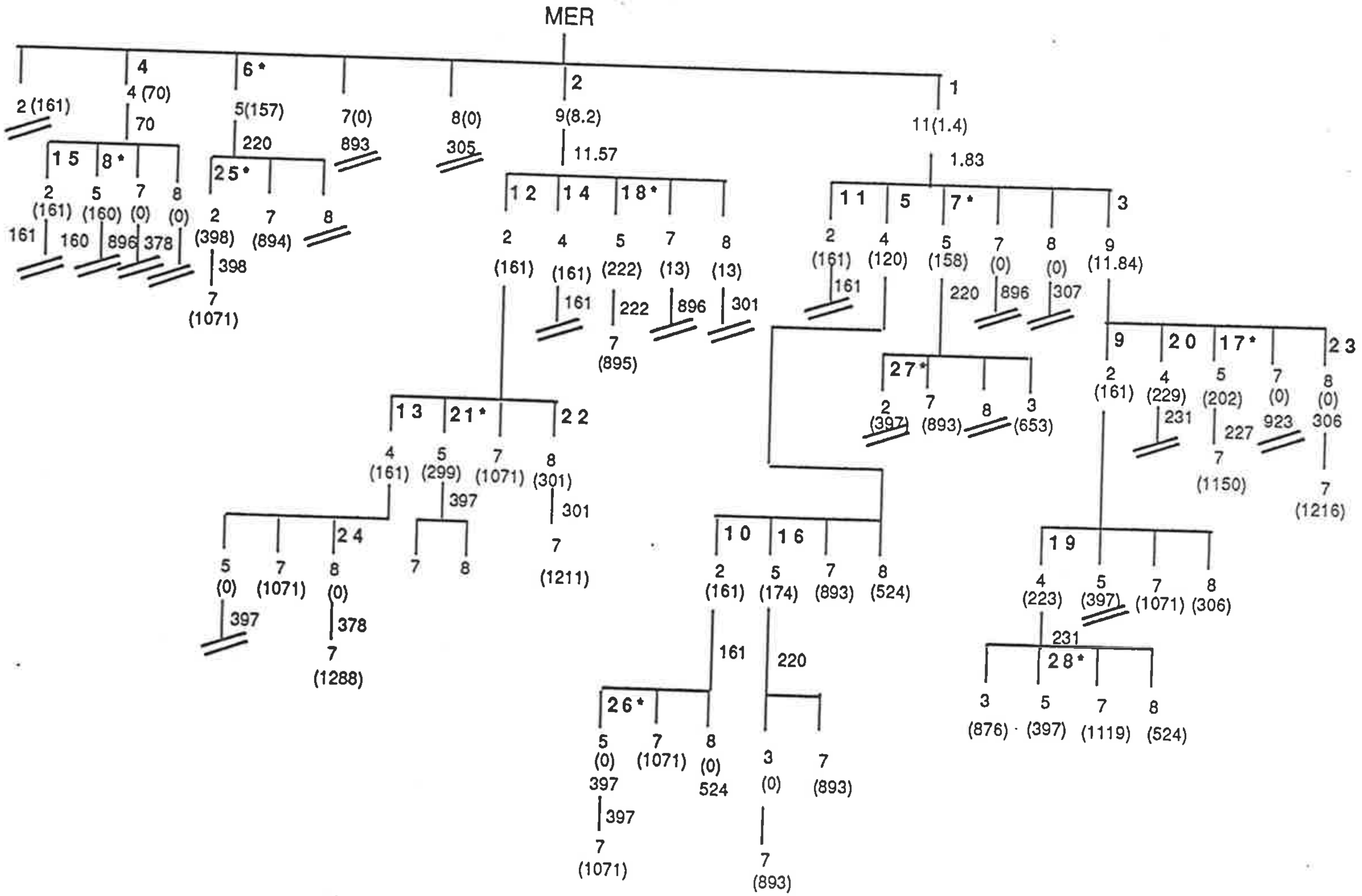


Figure 4.16: MER design for example 4.5



* Network seeded with dummy utility unit 14

Figure 4.17: 'Best-first' search tree for example 4.5

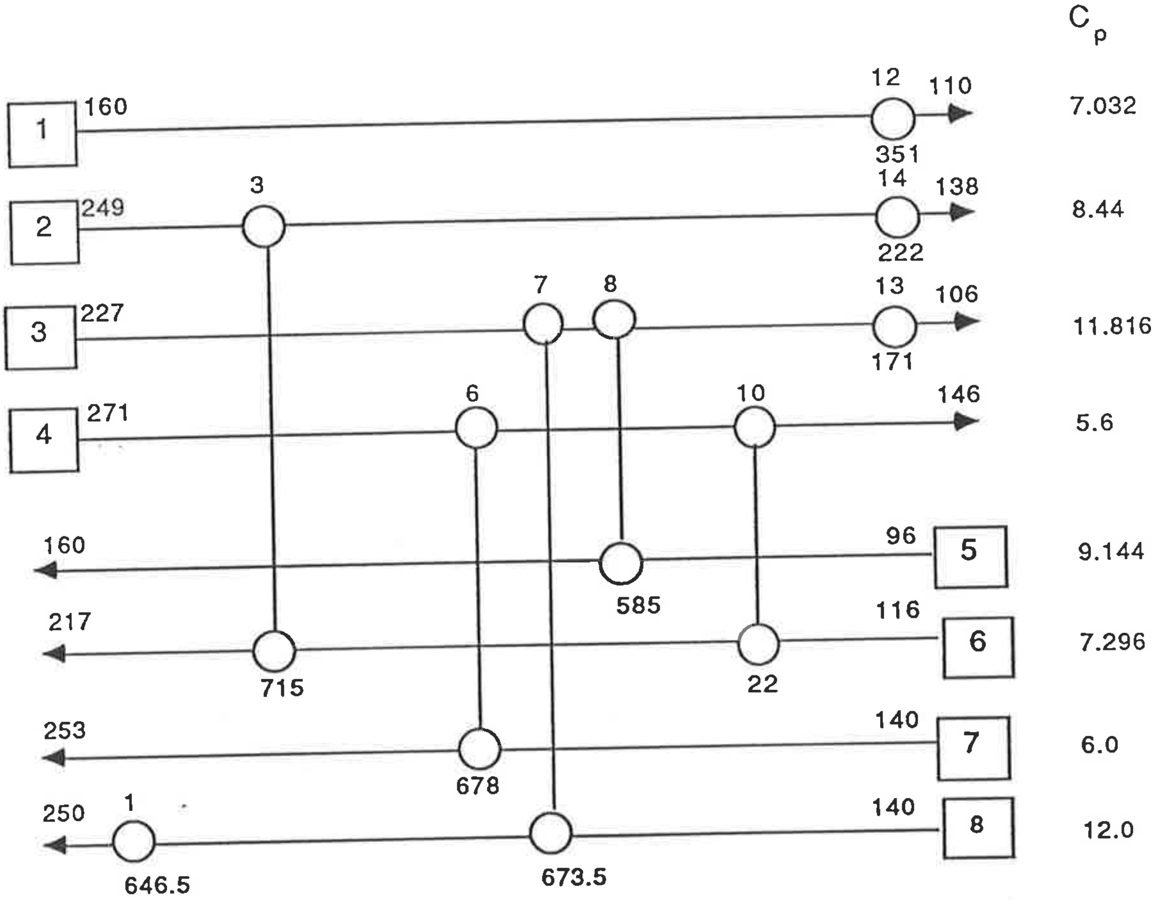


Figure 4.18: MNU design for example 4.5 with α = 397 kW

Table 4.7: Data for example 4.5

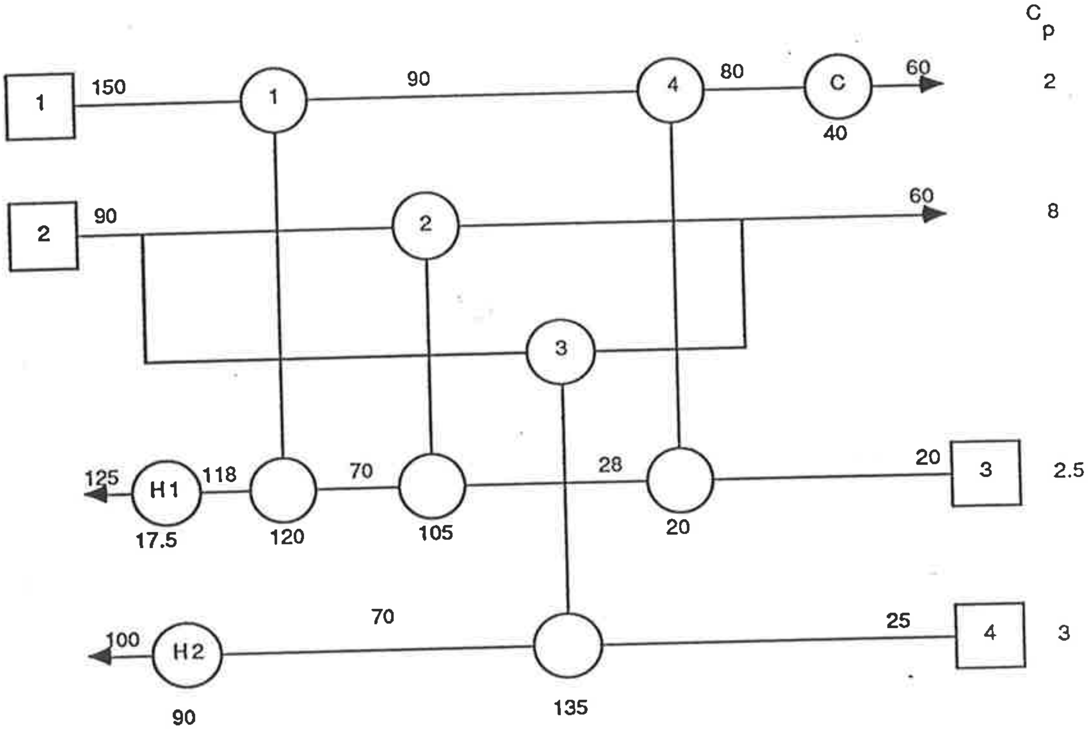
$\Delta t_{min} = 10$ K

Stream Number	C_p(kW/K)	T_s(°C)	T_t(°C)
1	7.032	160	110
2	8.44	249	138
3	11.816	227	106
4	5.6	271	146
5	9.144	96	160
6	7.296	116	217
7	6.0	140	253
8	12.0	140	250

4.8 Topology Traps

Consider the data of example 4.3 detailed in Table 4.4. An alternative design to that of Figure 4.7 is detailed in Figure 4.19. Table 4.8 reports the results obtained by loop breaking for both designs. This design, with six units, following the removal of unit 4, has an energy penalty of 4 kW while the resulting five unit design has an energy penalty of 65 kW. The previous design, with unit 5 eliminated, has an energy penalty of 6.7 kW for a six unit design and only 30kW for a five unit design. (Jones and Rippin [67] also found that the minimum energy penalty was 30kW for a U_{min} design for this data.)

From this example it can be concluded that different initial MER designs can lead to



Loop (1,4)

Figure 4.19: MER design 2 for example 4.3

Table 4.8: Summary of designs for example 4.3

Design 1 (ref. Figure 4.7)			Design 2 (ref. Figure 4.19)		
Units	α (kW)	Type	Units	α (kW)	Type
7	0	Split	7	0	Split
6	6.7	Split	6	4	Split
5	30	Split	5	65	Unsplit
5	30	Unsplit			

different final designs. Moreover, evolution of the network on the initial least energy penalty path does not guarantee that the next design evolved will also have the smallest energy penalty. At present there is no method by which we can choose the best initial MER designs for further evolution. This is due to the fact that a topology trap exists when an MER design evolves. The designer cannot easily switch from one MER design to the other MER design. This trap may cause the generation of entirely different designs on loop breaking. (Topology traps have also been identified [2] in relation to MER designs being dependent on the value of Δt_{min}). Hence, all the options should be investigated in detail. The 'best-first' strategy outlined above can be employed to investigate all possible designs evolved from the set of feasible initial MER designs. The search space would include all the MER designs. Under such circumstances, the design with minimum energy penalty which can be evolved from the initial set of designs will be found.

Table 4.9: Data for example 4.6 [2]

$\Delta t_{min} = 10$ K

Stream Number	C_p(kW/K)	T_s(°C)	T_t(°C)
1	0.10	327	40
2	0.16	220	160
3	0.06	220	60
4	0.40	160	45
5	0.10	100	300
6	0.07	35	164
7	0.35	85	138
8	0.06	60	170
9	0.20	140	300

Chapter 3 outlined a method for predicting optimum $\triangle t_{min}$. Ahmad and Linnhoff [2] also have reported a similar method. An MER design for this value of $\triangle t_{min}$ should require little or no optimization. However, the cost equations employed do not account for the piping foundation and the other extra costs associated with each unit in a complex configuration. If such additional costs are considered, a smaller number of units for the same energy consumption is likely to be a more attractive alternative. To illustrate this point, consider the data of Table 4.9. Assuming an exponential cost equation, Ahmad and Linnhoff have reported that the 'optimal' starting value of $\triangle t_{min}$ for this problem is 30 K. The same results are obtained using the method reported in chapter 3. Their final optimised design after evolution is detailed in Figure 4.20. This design has a hot utility consumption of 27.28 kW. It has 18 units, 24 shells, one split stream and a total network area of 6.33 m^2. The minimum exchanger approach temperature in this design is 17 K. An alternative design having the same energy consumption and minimum exchanger approach temperature is detailed in Figure 4.21. This design has 14 units, 29 shells, no stream splits and a total network area of 7.521 m^2. The topology was evolved by employing the dual approach temperature design method proposed in the next chapter. The design has fewer units and is less complex and consequently would probably be more attractive despite the slight increase in area and shells. Furthermore, it contains certain matches which are not found by using the pinch design method. It is very important to identify different topologies as they may have vastly different operability characteristics [44]. Thus, it would seem that due to the existence of topology traps, and as the final relaxed design is derived from the MER, a number of attractive alternative topologies would always be missed during the process of the initial MER design optimization. The designer should be aware of this fact and hence should investigate all possible alternatives.

4.9 Conclusions

This study has shown that the existing procedure for unit reduction in an MER (pinch) design network can lead to suboptimal designs with respect to energy as

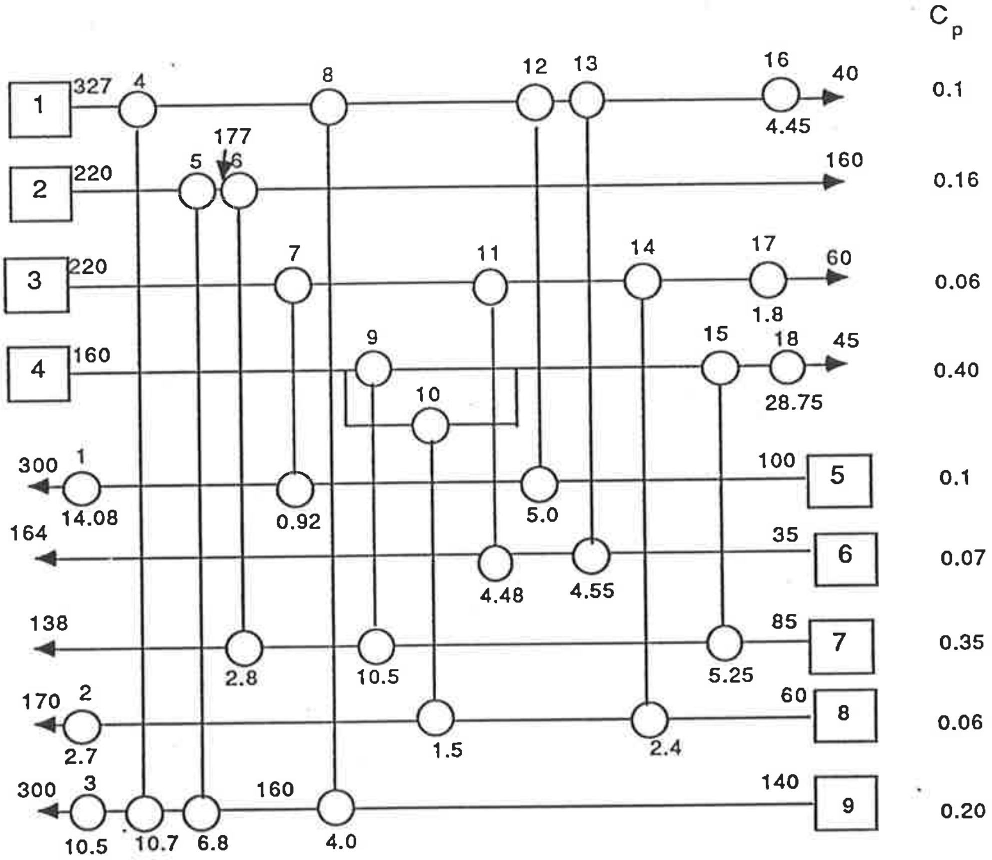


Figure 4.20: An optimal design for example 4.6 [2]

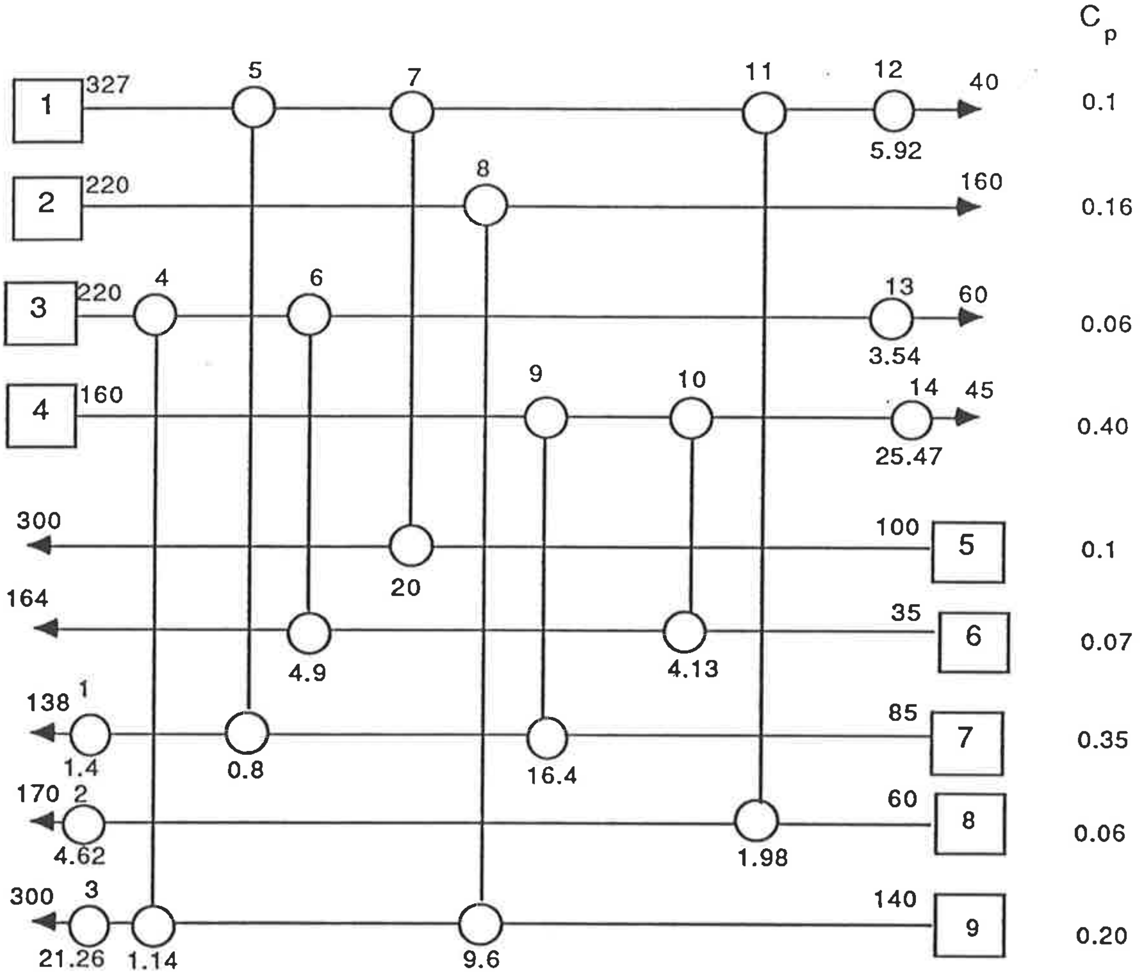


Figure 4.21: An alternative design for example 4.6 with the same energy consumption

unit reduction proceeds. A new strategy based on the 'best-first' search is developed. This method has been shown to be efficient in reducing the number of units with the least associated energy penalty. It is based on the fundamental understanding of loop-network interaction which has not been considered in the existing literature. The insights developed are a considerable aid to the designer, who still remains in complete control over the evolution of the network. In this chapter, the objective was to produce a final network design with minimum units but with an energy requirement as close as possible to the initial minimum energy requirement. It is the author's opinion that the generation of a globally cost optimum networks still remains an unresolved problem.

"Topology traps" with respect to the evolution of MER designs have been identified. The process of energy relaxation removes units from the initial MER (pinch) design. Thus, only the networks which could be derived from this initial design are examined. As units are always removed from the initial design (with the exception of seeding the network with a dummy utility exchanger), the number of designs that can be evolved is predetermined and fixed. Potential topologies having entirely different process-process stream matches, similar levels of energy consumption but lower unit requirements, may not be discovered at all. Hence it is very difficult to prove or to justify that any network initially generated by the pinch method has a globally optimum topology. This is a limitation of the pinch design method and not of the proposed strategy.

In the pinch design method, the matching rules are overly restrictive at the pinch point. These restrictive rules are only valid if the network energy consumption corresponds to the minimum requirement. Once energy is relaxed, the number of different possible matches increases (see next chapter). The nature of the matches are quite different from the "C_p rule" employed by the pinch design method. The designer should be aware of this fact and must try to investigate the different possible topologies. However, given that generation of MER (pinch) design is in common use, it is suggested that the 'best-first' search technique outlined in this chapter enables the designer to obtain the best possible outcome from an initial MER pinch design by energy relaxation to achieve unit reduction.

Little or no further optimization should be required if the initial MER network is generated at the optimum value of $\triangle t_{min}$ as seen in chapter 3 and as reported by Ahmad and Linnhoff [2]. However, in both cases simple cost equations (mainly exponential cost equations) are used which are not appropriate for analysis in a situation where better resolution is required. In real life, a reduced number of units for a given energy consumption will normally be the most attractive solution, with the exception of the designs featuring excessive stream splitting, mixing and bypassing. A globally optimal network will have energy consumption greater than the MER design but would feature fewer units. This indicates that an efficient method is required to predict the best combination of the total network energy consumption and minimum exchanger approach temperature prior to designing a network so that little or no further optimization is needed. However, both the methods can locate a good initial value of $\triangle t_{min}$.

Chapter 5

Dual-Temperature Design Method for the Synthesis of Heat Exchanger Networks

5.1 Introduction

Two general approaches to the problem of heat exchanger network synthesis have dominated the solution methods [109], viz. algorithmic methods [29,117] and evolutionary methods [16,25,91,96,100]. As the problem is to determine the optimal structure with interconnection of units, a so-called combinatorial problem has to be resolved. This has limited the algorithmic approach to simpler problems and hence the evolutionary methods have become dominant in the synthesis of commercial networks.

As noted before, two such major but competitive techniques are currently employed in network synthesis. The pinch design method formulated by Linnhoff and Hindmarsh [91] and the dual-approach temperature method advocated by SimSci$^{\mathrm{TM}}$ [25]. The pinch method is limited by the overly restrictive assumption of a global $\triangle t_{min}$ for the network and the individual exchangers. This constraint coupled with the rigid "C_p Rule" means that a significant sub-set of promising topologies is neglected because the possible pinch matches are confined to a sub-set of all the possible matches. The dual-approach temperature method of SimSci$^{\mathrm{TM}}$ generates a larger solution set but it is computationally cumbersome. The method referred to in the following work introduces the concept of a *pseudo-pinch*. This overcomes the deficiencies inherent in both methods while retaining the advantages. Thus, the network design is achieved by an efficient procedure, while the features of greater flexibility and control of the capital-energy trade-off inherent in the dual temperature approach are retained. Simple examples are presented to explain and illustrate the method.

A new cost equation is also introduced to enable evaluation and comparison of the generated topologies. The equations presented recognize the importance of considering units to be composed of multiple shells for the purpose of capital, installation and maintenance cost estimation. As well, an attempt has been made to account for the effects of stream splitting in terms of increased network complexity and cost. The problem of penalizing networks with poor operability is considered but a general solution to such problems is not derived.

The method proposed is both simple, efficient and provides the engineer with a better understanding of the strategic balance between complexity and increased utility consumption. It will ultimately lead to simplifications for the inclusion of multiple thermal utilities, heat and power integration and enable heavily constrained problems (such as retrofitting) to be handled more effectively.

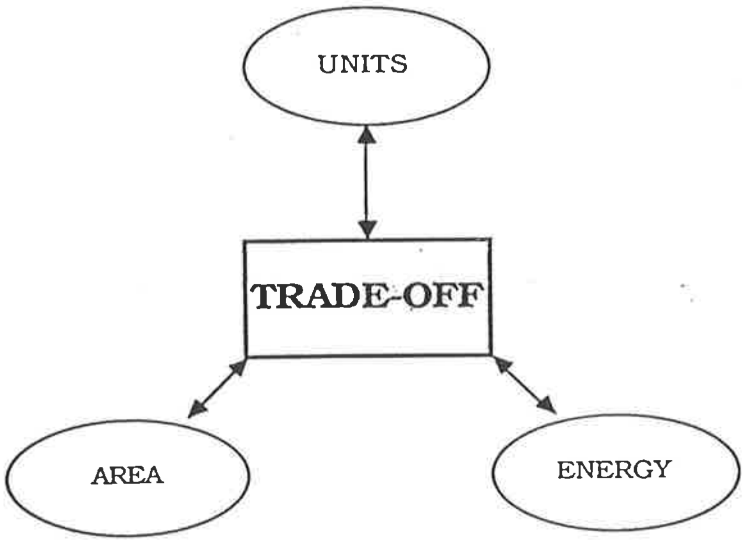


Figure 5.1: Trade-off considered by Masso and Rudd's formulation

5.2 Deficiencies of the Existing Problem Statement

The problem statement suggested by Masso and Rudd [105] was accepted by most researchers [16,29,56,91,96,88,112,117], who then proposed a variety of different design algorithms to accomplish the task. However, the above formulation is somewhat simplistic and fails to reflect the complexities of a real design situation. The trade-offs paramount to the aforementioned problem are summarized in Figure 5.1. The assumption of counter-current, single-pass shell-and-tube units is overly restrictive. In actual process sequences, units may possess multiple shells in series to avoid temperature cross-overs and to satisfy space constraints. Therefore, the number of shells is an important decision variable in the synthesis of the network. As well, practical networks may feature stream splits to achieve a specified energy consumption. This factor is neglected in the economic trade-offs fundamental to the above formulation.

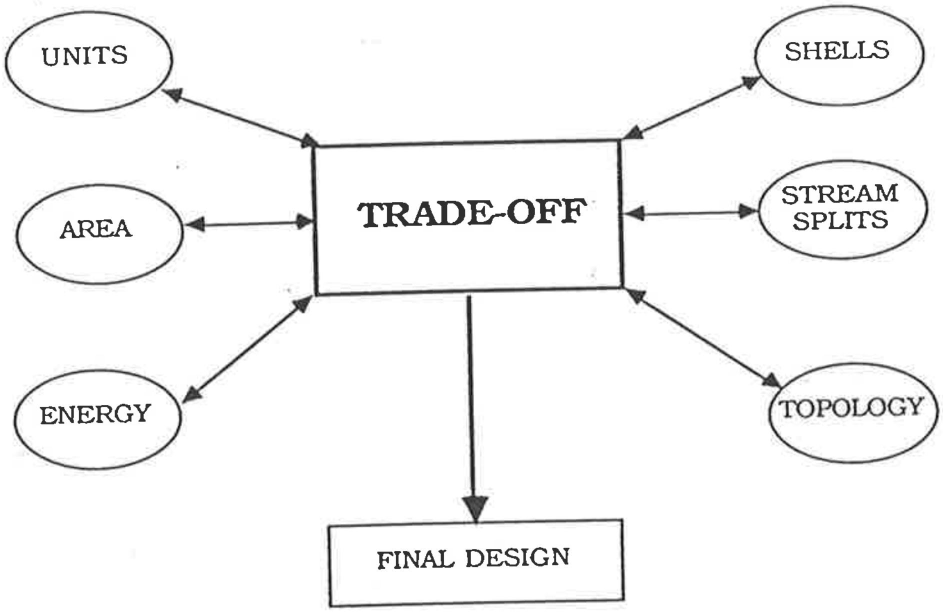


Figure 5.2: Trade-off in the modified formulation of heat exchanger network synthesis problem

A study of the available literature problems reveals that a variety of design topologies can be evolved based upon such a rudimentary model for evaluating the annual costs. Unfortunately, all designs [16,56,96,88,112,141] for specific problems reported in the literature have approximately the same annual cost and consequently other considerations will influence the final choice of the designer. Clearly, the operability of the network should be carefully evaluated. As is well documented, the operability of a network is strongly influenced by the final network topology [44].

Hence, the final decision regarding a network should account for all these factors. Obviously, the decision variables determining the optimal design of a heat exchanger network should be expanded to carefully consider the economic trade-off between units, area, energy, shells, stream-splits and topology (operability) as summarized in Figure 5.2.

The economic trade-off between the first five factors viz. units, area, shells, energy and stream splits can be readily quantified. However, it is very difficult to associate a cost with the topology. Ease of operability is a highly desirable goal for any process design but slightly different topologies have vastly different operability characteristics [44] and, given our current knowledge, it is extremely difficult to consider the operability of a network in the initial stages of design [18,133,153,45,143,11,48,80]. Presently, no method exists by which the operability cost of a network can be easily estimated or by which poor operability can be penalized. Therefore, a number of networks should be generated each having nearly the same total cost (quasi-optimal). These should be considered for detailed operability studies.

A modified version of Masso and Rudd's formulation is now proposed which accounts for the additional factors highlighted in the previous discussion.

5.2.1 Modified Problem Statement

The objective is now to *generate all feasible networks* having different topologies which are *quasi-optimal* with respect to the total cost.

The physical parameters characterizing the process streams and utilities remain unaltered. However, the equipment available to the designer will be expanded to include all categories of exchangers (multi-pass shell and tube units, cross-flow exchangers, split-flow arrangements, plate exchangers, etc.). The exchangers can be constructed in any appropriate material. Associated with each stream is an individual-film heat-transfer coefficient h_i. The contribution of each stream towards a heat-exchanger unit minimum-approach temperature is $\triangle t_{con}$.

5.3 Cost Equation: Deficiencies and Remedy

Different cost equations have been proposed for estimating the annual cost C_t of a given network. The most popular is the one used in Masso and Rudd's formulation given below [112]:

$$C_t = \xi \left[\sum_i a\, A^b_{Ei} + \sum_i a\, A^b_{Hi} + \sum_i a\, A^b_{Ci} \right] + \left[\sum_k \sum_l \{ U_k\, S_{ukl} \} \right] \tag{5.1}$$

Here ξ is the capital-recovery factor required to annualize the initial cost of the network. The value of b in equation(4.1) is frequently assumed to be a fraction (0.6). For all values of b less than unity ($0 \leq b \leq 1$), Nishida et al. [112] have reported the following inequalities :

$$\begin{aligned} a(A^b_{H1} + A^b_{H2} + A^b_{H3} + \ldots + A^b_{Hm}) &\geq \\ a(A_{H1} + A_{H2} + A_{H3} + \ldots + A_{Hm})^b & \qquad (5.2) \\ a(A^b_{H1} + A^b_{H2} + A^b_{H3} + \ldots + A^b_{Hm}) &\geq \\ a(A_{H1} + A_{H2})^b + a(A_{H3} + \ldots + A_{Hi})^b + a(A_{Hi+1} + \ldots + A_{Hm})^b & \qquad (5.3) \end{aligned}$$

These inequalities suggests that *"the investment cost of exchangers can be reduced if several exchangers can be combined together as a single one, or a smaller number of exchangers are used, keeping the total heat transfer area for the whole network constant."* Linnhoff and Flower [96] have also noted a similar conclusion.

However, this observation has led to a misconception that networks featuring minimum number of units are optimal for a given utility consumption. This concept was first proposed by Hohmann [56] and later utilized by Boland and Linnhoff [16] as well as by Wood et al. [160]. However, Colbert [25] observed that for shell and tube exchangers, the total number of exchanger shells may increase or decrease as the number of units is reduced. This will also change the F_t factors and alter the total area of the network. Therefore, whilst the minimum number of units target is a useful heuristic, it can be misleading for locating a practical optimal configuration.

Another disadvantage inherent in the above equation and noted by Linnhoff and Flower [96] is that it predicts the least cost if the total surface area is distributed as unevenly as possible over a given number of separate exchangers. To avoid such difficulty, Linnhoff and co-workers [96,88] have recommended the two cost equations given below:

$$\begin{aligned} C_u &= aA^b_{\text{lower bound}} + c \\ A_u &\leq A_{\text{lower bound}} \qquad (5.4) \\ C_u &= aA^b_u \qquad (5.5) \end{aligned}$$

where A_u = area per unit.

Unfortunately, these equations neglect the fact that the number of shells within a unit affects the cost, but they have a practical basis as smaller exchanger units will tend to have a constant installation cost. As well, both of the previous cost formulations neglect the cost associated with stream splits, the cost of associated pipe work, of pumps, and the control valves used in the network.

As noted, the capital cost of a network, depends on the total area, number of units and shells over which it is distributed and the total pipe work required. A new cost equation for predicting the capital cost of a network is proposed (Appendix E). The equation is based upon the concept of a 'cluster' of exchangers (located in reasonably close proximity) comprising the network and it identifies three essential contributions to the cost, namely

- cost of individual units (composed of shells) plus associated local piping and instruments
- installation costs
- additional piping and maintenance costs associated with stream splitting.

Having a reliable method for costing networks will avoid the development of networks which achieve an inappropriate target e.g. the minimum number of units target is not always cost effective [25].

It is now proposed to employ this new cost equation in combination with a new network design algorithm to synthesize and evaluate a wide variety of network topologies. By way of introduction, let us consider the current "state of the art".

5.4 Existing Design Procedures

Numerous design methods have been proposed in the past decade for synthesizing heat exchanger networks (see chapter 2). These design methods can be broadly classified into two categories:

1. Mathematical programming methods.
2. Systematic evolutionary methods.

The search methods [24,29,117] based on mathematical programming techniques require a large amount of computing time even for small problems. They are normally very complex and require considerable mathematical expertise. However, so far these methods seem to have problems in producing 'practical networks' for industrial problems. The systematic evolutionary methods develop an initial network with appropriate criteria which is then modified towards a final optimal practical network. In the last five years, systematic evolutionary methods have been accepted as the best available method to generate alternative networks. They are simple to comprehend and implement.

Two such design methods have become popular among practising engineers viz. the pinch design method of Linnhoff and Hindmarsh [91] and the dual -approach temperature method advocated by SimSci^{TM} [24,25]. The essentials of both design methodologies are outlined in Figure 5.3 and Figure 5.4.

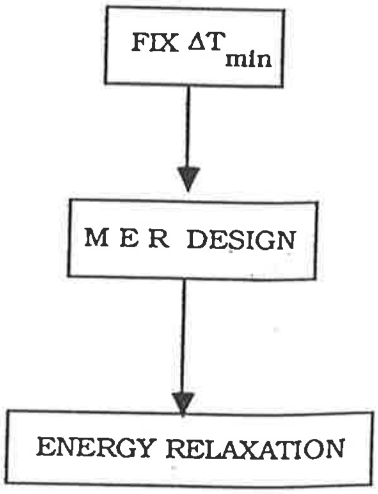


Figure 5.3: The pinch design method

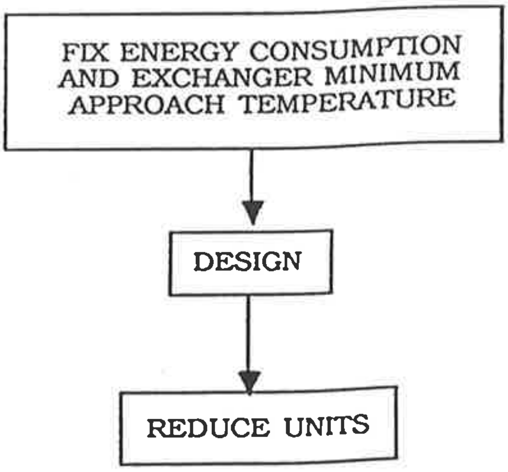


Figure 5.4: The dual-approach temperature design method

5.4.1 The Pinch Design Method

The pinch design method is based on a thermodynamic analysis of the problem. The minimum utility requirements are predicted by employing an enthalpy balance at a prescribed value of the minimum approach temperature, $\triangle t_{min}$. This leads to the identification of the most constrained region of the problem, ‘ the pinch ’. The pinch point divides the network into two independent subproblems. Each subproblem may then be designed independently, commencing at the pinch and developing it by moving outwards towards the hot or cold end.

The matches are allocated by following a set of heuristic guidelines detailed by Linnhoff and Hindmarsh [91]. The two designs are then merged to give a preliminary network which has the predicted minimum utility requirement which is not particularly suitable for practical application. This preliminary design, is an appropriate antecedent for evolution to reduce the number of units usually at the expense of increased energy consumption. In the previous chapter a technique (Loop network interaction algorithm, LONITA) to identify *the minimum energy penalty* path along which energy should be relaxed was developed. It also found that ‘ topology traps ’ exist during such evolution and as a consequence, the multiple possible designs cannot be readily identified. Furthermore, the final network of the evolution depends on the particular initial maximum energy recovery (MER) design chosen.

Using the above pinch technique, flexibility is lost once the initial design is generated, and the *a priori* prediction of the possible energy penalty and consequent trade-offs are not possible. Despite these drawbacks, the method is very widely applied. Reasons for its wide acceptance include :

- The design's partial control over the evolution process.
- It is easily understood and is suited for hand calculations.
- It can be used to identify a restricted set of alternatives quickly [subject to the limitations mentioned above].

- The ready application of pinch technology to the study of networks in the general process environment

5.4.2 The Dual-Approach Temperature Method

The dual-approach temperature method defines two approach temperatures, namely: Heat recovery approach temperature (HRAT) and exchanger minimum approach temperature (EMAT) with HRAT $\geq$ EMAT. The heat recovery approach temperature (HRAT) is identical to $\triangle t_{min}$ employed by the pinch design method in the sense that it determines the closest approach of the composite curves and hence the required input from hot utility. In the dual-approach temperature method, the values of HRAT (and hence hot utility requirement) and EMAT are chosen by the designer before commencing the design. This is in contrast to the pinch design method, which utilizes a global value of $\triangle t_{min}$ (i.e. HRAT=EMAT) and then relaxes the energy consumption of the network (with the obvious implication of increase in $\triangle t_{min}$).

The name HRAT (the heat recovery approach temperature) is the minimum approach temperature between the composite curves as illustrated in Figure 5.5. This term is unwieldy and provides little physical insight, we therefore propose to rename HRAT as $\triangle t_{Nmin}$ (network minimum $\triangle t$). For a given value of $\triangle t_{Nmin}$ (HRAT), the utility requirement can be determined from the composite curves. Alternatively, the *problem table* [96] can also be employed to calculate this requirement by setting the value of pinch temperature at $\triangle t_{min} =$ HRAT ($\triangle t_{Nmin}$).

Similarly, EMAT (the exchanger minimum approach temperature), which is the minimum allowable approach temperature is renamed as $\triangle t_{Emin}$ (exchanger minimum $\triangle t$). $\triangle t_{Emin}$ (EMAT) must always be less than or equal to $\triangle t_{Nmin}$ (HRAT). To understand the terminology, consider the network shown in Figure 5.6. The total hot utility consumption for the network is 4900 kW. This corresponds to the energy target with $\triangle t_{Nmin}$ (HRAT) = 32K using the composite curves. However, exchanger 2 has a minimum temperature approach of 20K. Thus, $\triangle t_{Emin}$ (EMAT) = 20K for the network.

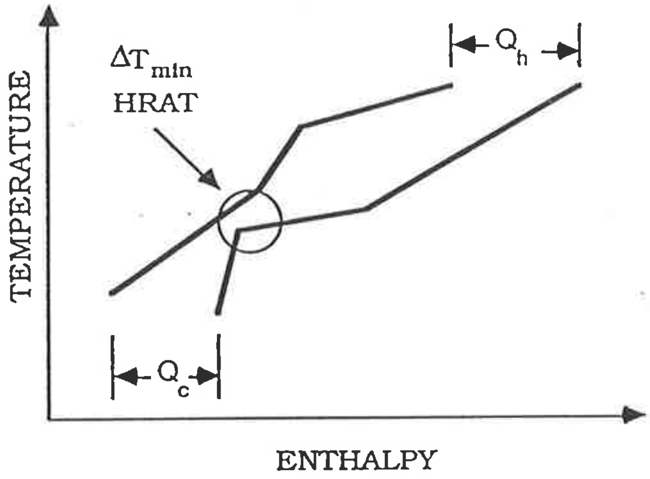


Figure 5.5: HRAT, heat recovery minimum approach temperature

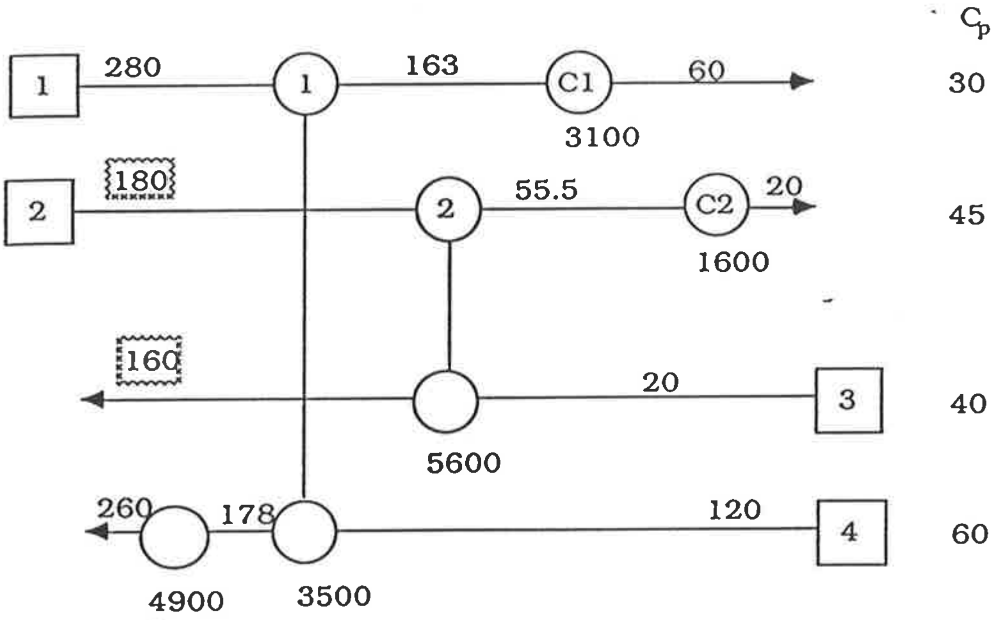


Figure 5.6: Network for example 5.1 with $\Delta t_{Emin} = 20K$, $\Delta t_{Nmin} = 32K$, and relative cost = 244.13

The dual-approach temperature method [25] is similar to the temperature-interval method proposed by Linnhoff and Flower [96]. Δt_{Emin} is used to define the temperature intervals. This division creates a large number of subnetworks which are then independently designed. The initial design is evolved using either the evolutionary development (ED) rules of Linnhoff and Flower [96] or the formal loop-breaking procedure of Su [141,142]. This method requires a computer solution even for moderately-sized problems. As well, the problem of topology traps exists and it is therefore not possible to quickly identify all possible combinations for given values of Δt_{Nmin} and Δt_{Emin}. The initial design has a large number of units and loops. Consequently, it is more difficult to generate compared with the pinch design algorithm. Furthermore, no definite criterion exists for the identification of stream splits.

However, the concept is very powerful as the designer retains complete control over the energy consumption of the network. This is in contrast to the pinch design method where the energy consumption increases following loop breaking and is determined by the new topology and not by the designer. There is no target with which to judge whether such an increase is reasonable and so alternative designs have to be investigated. Another advantage in using the dual-approach temperature method is the reduction in the number of shells and units. As well, unnecessary stream splits may be avoided, making a more practical network with better operability characteristics. This may result in substantial decrease (20%) in the capital cost for a fixed energy consumption, representing millions of dollars savings in industrial applications [115].

Figure 5.7 and Figure 5.8 compares the network simplifications and trade-offs inherent in the two methods.

Here, a new method is proposed which is an amalgamation of these two established procedures and retains the advantages of both these techniques. The method divides the problem into only two subproblems which can be thermodynamically independent, depending on the values of Δt_{Nmin} and Δt_{Emin}. This results in a substantial saving in computation effort. It is described in detail in the following sections.

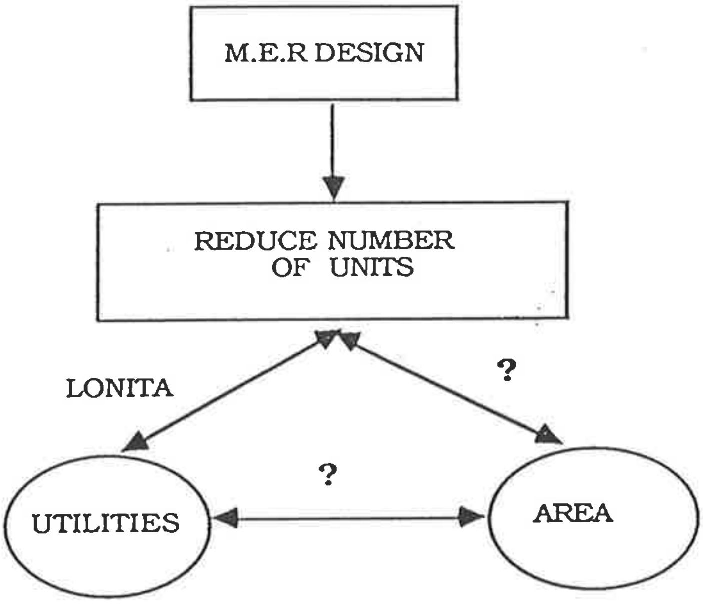


Figure 5.7: Trade-off's in the pinch design method

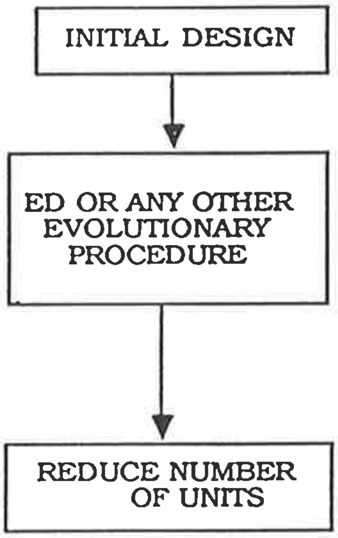


Figure 5.8: Trade-off's in HEXTRAN.

5.5 Pinch Principle and the Pinch Design Method: Difficulties and Extensions

Umeda et al. [154]and Linnhoff and Flower [96] independently proposed the pinch principle. Umeda located the pinch using the composite curves. He defined it as the point of closest approach of the hot and cold composite curves. Linnhoff and Flower defined the pinch as the point of zero heat flow in the problem table.

Linnhoff and Vredeveld [90], Linnhoff and Hindmarsh [91] have suggested that: *" designs meeting an energy target exhibit zero heat flow across the pinch. Sub-optimal designs* (with respect to energy consumption) *exhibit a heat flow across the pinch which corresponds to excess utility consumption of both hot and cold."*

This statement apparently contradicts the philosophy of the existing pinch design method. As previously noted in Figure 5.3, the pinch design method recommends relaxing this maximum energy recovery network to decrease the capital cost. The result is an *" energy leakage "* across the " initial " pinch leading to the apparent violation of the original pinch concept [15].

Relaxing the energy (i.e. increasing the hot utility) can also be viewed as " pulling " the composite curves apart. This increases the " passing " hot stream temperatures or lowers the " passing " cold stream temperatures at the new pinch point. Clearly, the new pinch point has a greater $\triangle t_{pinch}$ than the initial $\triangle t_{Nmin}$ at the pinch.

Boland [15] has also pointed out that *" difficulties do exist in terms of handling the pinch concept in context of global $\triangle t_{Nmin}$ and designing the exchangers in the network with different approach temperatures "*. Here, we propose to modify the basic concepts and overcome such difficulty.

The pinch design method divides the network into two independent subproblems. This division is done at the pinch point where the problem is most constrained [42]. The resulting subproblems are in enthalpy balance. To achieve a capital energy trade-off, it then relaxes an initial global value of $\triangle t_{Nmin}$ for the network whilst maintaining a $\triangle t_{Emin} = (\triangle t_{Nmin})_{initial}$ as an approach limit for individual exchangers. Unfortunately, the resulting ' optimal ' network has an energy consumption defined by the new global value of ' $\triangle t_{Nmin}$ ' with individual exchangers are still limited by the original $\triangle t_{Emin}$. Thus, supporting the use of two clearly defined approach temperatures viz. $\triangle t_{Nmin}$ and $\triangle t_{Emin}$ (ie. HRAT and EMAT as defined by SimSci^{TM} [25]).

Clearly, these two viewpoints need reconciliation and finding a method incorporating the best features of both methods is desirable. The limitations of the energy relaxation and the necessity for a computer solution could be overcome by combining the $\triangle t_{Nmin}$ and $\triangle t_{Emin}$ concept with the characteristics of the pinch design method. The key simplification of pinch design method is the division of the original problem into only two subproblems which are in enthalpy balance. Such a feature can be incorporated into the dual-approach temperature method by defining a *pseudo-pinch* as follows.

5.6 The Pseudo-Pinch "Point"

5.6.1 Location

Initially, two sets of composite curves are generated using $\triangle t_{Nmin}$ and $\triangle t_{Emin}$ with $\triangle t_{Nmin}$ selected such that $\triangle t_{Nmin} \geq \triangle t_{Emin}$. Both sets will have different energy consumptions denoted as (EC).

As $\triangle t_{Emin} \leq \triangle t_{Nmin}$, therefore $EC_{\triangle t_{Emin}} \leq EC_{\triangle t_{Nmin}}$

If $\triangle t_{Emin} = \triangle t_{Nmin}$, then a single set of composite curves is generated, implying an identical energy consumption and conventional pinch point.

Let us define the energy difference α (Figure 5.9 and Figure 5.10) as

$$\alpha = EC_{\triangle t_{Emin}} - EC_{\triangle t_{Nmin}}$$

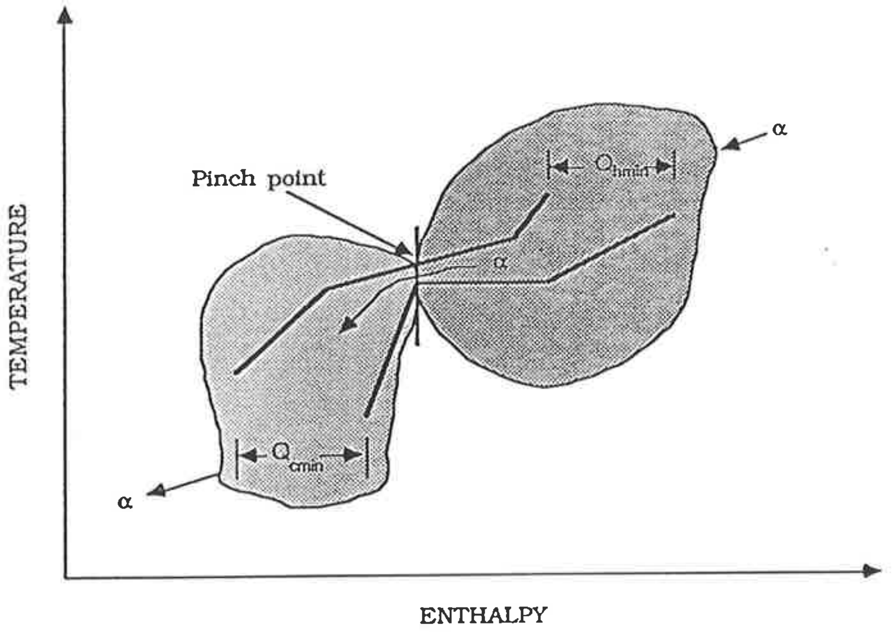


Figure 5.9: Energy relaxation with heat transfer across the pinch point

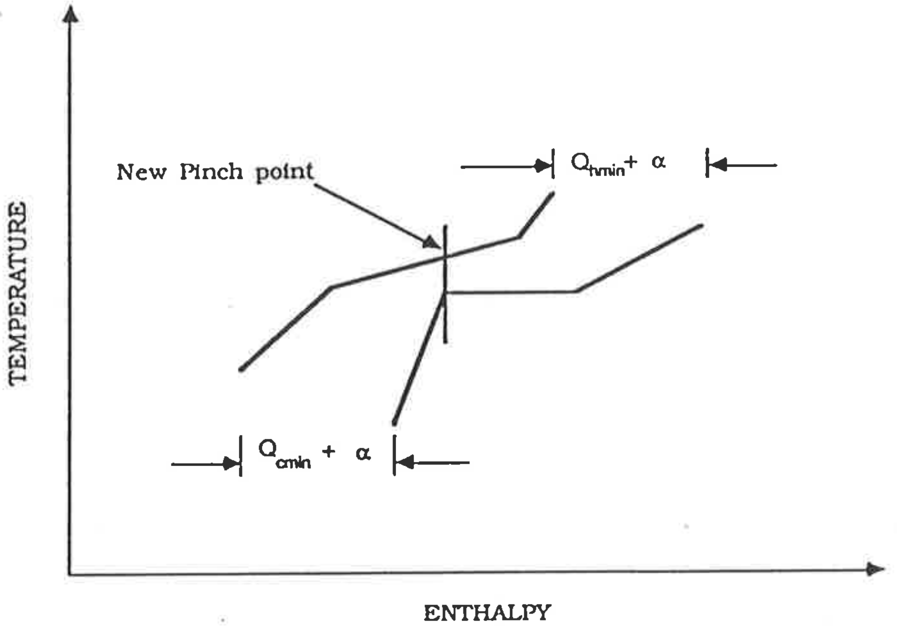


Figure 5.10: New pinch point with minimum energy consumption + α

As the network is designed employing two approach temperatures, a new interpretation of the problem could be:

> As $\triangle t_{Emin}$ is less than $\triangle t_{Nmin}$ an amount of energy α traverses the $\triangle t_{Emin}$ conventional pinch point. This can be compensated by energy transferred upwards across the pinch due to the fact that heat exchange is allowed at temperature differences as low as $\triangle t_{Emin}$ between streams. The maximum amount of this upward transfer which can be achieved is the value of α defined above. This represents additional flexibility in stream matching by providing for upward and downward transfer which is permitted by the reduced $\triangle t_{Emin}$ between streams while the total energy consumption remains fixed at $EC_{\triangle t_{Nmin}}$, which in turn is defined by the network approach temperature $\triangle t_{Nmin}$.

A pseudo-pinch "point" (actually a set of stream temperatures) is defined so that the stream temperatures at this "point" allow the problem to be partitioned as shown in Figure 5.11. Thus, the two parts of the network are in enthalpy balance with the utility consumption determined by $\triangle t_{Nmin}$. (As explained later there is no unique set so some heuristic guidelines are required). However, the approach temperatures between the streams at the pseudo-pinch point are $\geq \triangle t_{Emin}$. (The pseudo-pinch would be the same as a conventional pinch if $\triangle t_{Nmin} = \triangle t_{Emin}$). As the energy consumption for $\triangle t_{Nmin}$ exceeds that for $\triangle t_{Emin}$ by α, the network may be considered to have an energy penalty α for designs with approach temperatures as low as $\triangle t_{Emin}$ as implied by Figure 5.11. This design procedure proposes methods for determining the temperatures for streams at the pseudo-pinch point. The network designs for these two subproblems may then proceed independently as in the conventional pinch design method.

(The term pseudo-pinch has also been used by Rev and Fonyo [128] in work extending the pinch design method. They use the expression differently to mean that a real pinch is almost implied by the original data or arises following the selection of matches for heat exchange).

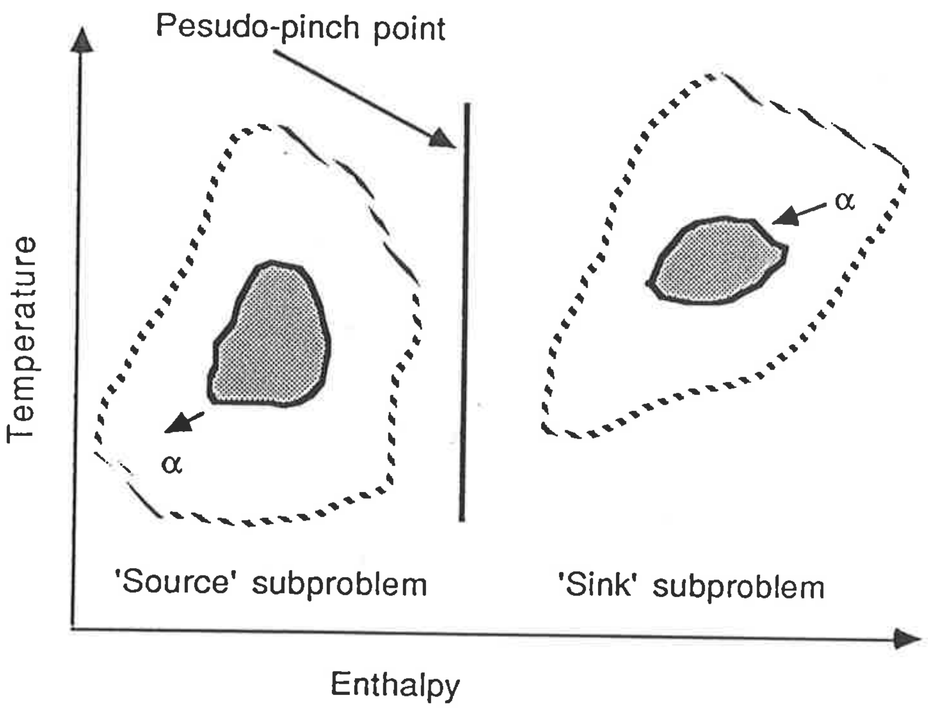


Figure 5.11: Pseudo-pinch division of the problem

The subproblem above the pseudo-pinch is titled the ‘ **sink** ’ problem as only heating utility is required. Likewise, the below pseudo-pinch problem is called a ‘ **source** ’ problem.

The changes in slope of the composite curves, which occur at the real pinch point, require that normally (at least) one hot or cold stream enters at a real pinch point temperature [42]. *This stream's starting temperature determines the basis for the pseudo-pinch "point".* To determine the pseudo-pinch point temperatures with α

units of heat transferred across the real pinch point (at $\triangle t_{Emin}$) the following heuristics are used:

1. Pseudo-Pinch Point Temperatures having $\triangle t = \triangle t_{Emin}$

   If a hot stream with a starting temperature T_{hs} determines the real pinch point for $\triangle t_{Nmin}$ or $\triangle t_{Emin}$, then this stream is also assumed to be at the pseudo-pinch point, with all the cold stream temperatures given by T_{hs} - $\triangle t_{Emin}$. Likewise, if a cold stream entrance determines the real pinch point, then the pseudo-pinch temperatures are given by $T_{cs} + \triangle t_{Emin}$. At times, it may be possible that different streams may determine the real pinch point the values of both $\triangle t_{Nmin}$ and $\triangle t_{Emin}$. In such a situation different topologies would result and all possible configurations should be investigated. For all the examples in this chapter, $\triangle t_{Emin}$ is used for finding the stream which determines the real pinch point.

2. Pseudo-pinch point temperatures with $\triangle t > \triangle t_{Emin}$

   The α units of heat transferred across the real pinch point will increase the pseudo-pinch point $\triangle t$'s for some stream combinations. Assuming that a hot stream determines the real pinch point, the possible strategies for allocating the α units are as follows:

   (a) If there are N other hot streams with $T_{hsi} \geq T_{hsp}$ then $\alpha_i = \alpha/N$ is allocated to each of these streams so that their pseudo-pinch point temperatures are increased by $\alpha/(NC_{pi})$.

   This heuristic will be employed in the examples in this chapter.

   (b) The temperatures of the other real-pinch point hot streams could be equally increased by $\alpha/\sum_i C_{pi}$.

   (c) The magnitude of α_i could be determined by using weighting factors, perhaps inversely proportional to the stream film heat transfer coefficients.

   (d) Opportunities may exist to assign α_i so as to force stream ' slipping ' [102], thereby reducing the target minimum number of units.

   (e) Any other strategy which divides the problem into two parts which are in enthalpy balance with $\triangle t_{Emin} \not> \triangle t_{Nmin}$.

Table 5.1: Data for example 5.2 [102]

Stream Number	C_p(kW/K)	T_s(°C)	T_t(°C)
1	156.3	85	45
2	50.0	120	40
3	23.9	125	35
4	1250.0	56	46
5	1500.0	90	85
6	50.0	227	75
7	466.7	40	55
8	600.0	55	65
9	195	65	165
10	81.3	10	170

3. Alternatively, if the real pinch is determined by a hot stream then the pseudo-pinch temperature of all the hot streams may be fixed at this temperature T_{hsp} and the α allocated employing the above heuristics to all the cold streams at a temperature T_{hsp} - $\triangle t_{Emin}$.

T_{hsp} is the 'real' pinch temperature of the hot stream.

Example 5.2

To illustrate the use of the aforementioned heuristics for distributing α and for determining the pseudo-pinch temperatures, let us consider a problem proposed by Linnhoff and Ahmad [102]. The relevant data is presented in Table 5.1.

Let $\triangle t_{Nmin} =$ 15 K and $\triangle t_{Emin} =$ 10 K. The ' real' pinch point using $\triangle t_{Emin}$ as the network minimum approach is determined by stream 4. Hence, the cold stream pseudo-pinch temperature is 46°C. The pseudo-pinch temperature of stream 4 is 56°C (46 + 10). The value of α is 2478 kW. There are five hot streams above the ' real ' pinch of which only three (1,2,3) exist at the pinch. Clearly, these three streams are the likely candidates to transfer the heat load across the ' real ' pinch. According to the simplest heuristic for assigning α_i, each of the streams (1,2 and 3) will transfer an additional 826 kW across the ' real ' pinch. The resulting pseudo-pinch temperatures are tabulated in Table 5.2. An alternative strategy might be to force stream 3 to ' slip ' across the ' real ' pinch by assigning α_3 = 1649 kW. The residual α (828.9 kW) could then be transferred by streams 1 and 2. Table 5.2 lists the different possible pseudo-pinch temperatures for these choices. Also included is the case where the α_i's are allocated inversely proportional to the individual film coefficients h_i (where $h_1 : h_2 : h_3 = 1 : 3.1 : 1.367$). This example illustrates the complete control and flexibility possessed by the designer when assigning the pseudo-pinch temperatures to generate and then investigate different topologies.

A counter example where a cold stream determines the pseudo-pinch location can be derived by reference to Table 5.3.

Here, the cold stream 4 determines the pinch point, so the hot stream pseudo-pinch temperature is fixed at 140°C ($\triangle t_{Emin} =$ 20 K). The cold stream 3, in this case is responsible for the heat transfer across the pinch. The value of α is 900 kW. Thus, the pseudo-pinch point of the cold stream 3 will be 97.5°C (120 - 900/40).

Table 5.2: Pseudo-pinch temperatures (T_{pp}) for example 5.2

$\Delta t_{Nmin} = 15$ K and $\Delta t_{Emin} = 10$ K

Stream Number	α_i^1	T_{pp}(°C)	α_i^2	T_{pp}(°C)	α_i^3	T_{pp}(°C)
1	826	61	414	58	1200	64
2	826	73	414	64	400	64
3	826	91	1649	125	878	93
4		56		56		56
5		85		85		85
6		75		75		75
7		46		46		46
8		55		55		55
9		65		65		65
10		46		46		46

1. $\alpha_i = \alpha/N$;
2. stream 3 ‘slipped’;
3. α_i allocated inversely proportional to h_i.

Table 5.3: Data for example 5.1

$\Delta t_{Emin} = 20$ K

Stream Number	C_p(kW/K)	T_s(°C)	T_t(°C)
1	30	280	60
2	45	180	20
3	40	20	160
4	60	120	260

5.7 Design of the Sink Subproblem

5.7.1 Feasibility Criteria at the Pseudo-pinch

As the problem constraints are relaxed at the ‘ real ’ pinch by passing heat across it, a wide variety of network topologies can be generated. Let us follow the pinch-design philosophy of commencing our design at the pseudo-pinch. As there are only a few essential matches to be made at the pseudo-pinch point, all the options available to the designer can be readily identified. The designer, utilizing his process knowledge and experience can now select the necessary matches. These could include any imposed and constrained matches required for a safe, controllable and practical network or any other preferences the designer may have. To assist the designer, a set of feasibility criteria are developed below to indicate to the designer when to split the streams and to guide him in executing the proper trade-offs.

5.7.2 Number of Process Streams and Branches

In a ‘ real ’ pinch situation, the stream population is compatible with a minimum utility design only if a pinch match can be found for each hot stream above the ‘ real ’ pinch. The situation is illustrated in Figure 5.12 where stream splitting is unavoidable. However, for the pseudo-pinch situation, splitting may not be necessary as demonstrated in Figure 5.13. This results from the relaxation of the ‘ real ’ pinch temperatures resulting in an increase in the available driving forces for the pseudo-pinch matches.

It is exceedingly difficult to determine in advance if stream splitting is necessary. Hence, two approaches are suggested. The first approach is identical to the pinch design method outlined previously. The stream splits may then be removed once the initial design is generated. This will be discussed later. In the second approach, we place the pseudo-pinch matches and see if the unmatched streams at the pseudo-pinch can be satisfied. If the streams are matched with violation of $\triangle t_{Emin}$ then split a stream and re-do the pseudo-pinch matching. Thus, immediately adjacent to

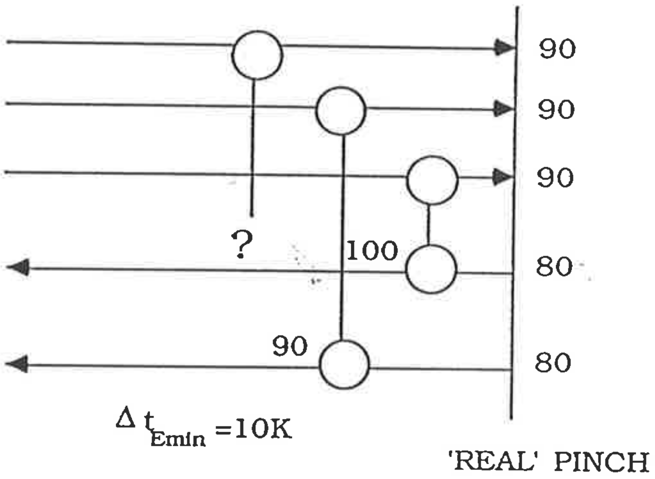


Figure 5.12: Stream population feasibility criteria in above 'real' pinch problems [100]

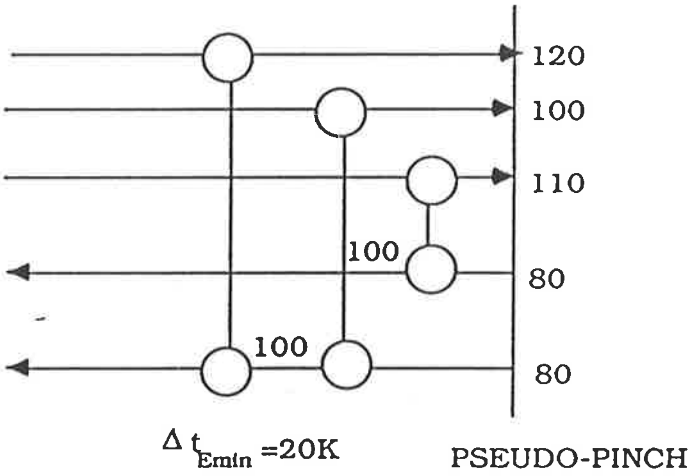


Figure 5.13: Stream splitting may not be necessary in pseudo-pinch problems

the pseudo-pinch for the sink problem, the design philosophy is summarized as

```
SINK PROBLEM
START
If $N_h \geq N_c$
split a cold stream
place the matches
try removing the split streams later
```

OR

```
SINK PROBLEM
START
If $N_h \geq N_c$
place pseudo-pinch matches
match the remaining streams without violating $\Delta t_{Emin}$ constraint
All streams at pseudo-pinch satisfied ?
if not usually split a cold stream and then go to start
```

5.7.3 The Temperature Feasibility Criteria

Four temperature profiles are possible for a match at the pseudo-pinch as shown in Figure 5.14. These profiles are for the 'sink' subproblem. The match illustrated in Figure 5.14(a) possesses the same characteristics as that of an above 'real' pinch match. However, for a pseudo-pinch, other matches of the type illustrated in Figure 5.14(b), (c) and (d) are also possible. Therefore, the following criteria exist at the pseudo-pinch which determine the maximum heat load Q_{max} for a match between a hot and cold stream.

Given that the amounts of heat available above the pseudo-pinch for the hot and cold streams are

$$Q_h = C_{ph}(T_{hs} - T_{hpp})$$

$$Q_c = C_{pc}(T_{ct} - T_{cpp})$$

then Q_{max} is determined by one of the following criteria, each of which correspond to Figure 5.14a-d

(a) $C_{ph} \leq C_{pc}$; $Q_{max} = min(Q_h, Q_c)$

(b) $Q_{max} = Q_h \leq Q_c \leq C_{pc}(T_{hs} - \Delta t_{Emin} - T_{cpp})$

(c) $Q_{max} = Q_c \leq Q_h \geq C_{ph}(T_{ct} + \Delta t_{Emin} - T_{hpp})$

(d) $Q_{max} \leq Q_c \leq Q_h = C_{ph}(T_h - T_{hpp})$

where $T_h = \frac{(C_{ph}T_{hpp}) - C_{pc}(\Delta t_{Emin} + T_{cpp})}{(C_{ph} - C_{pc})}$

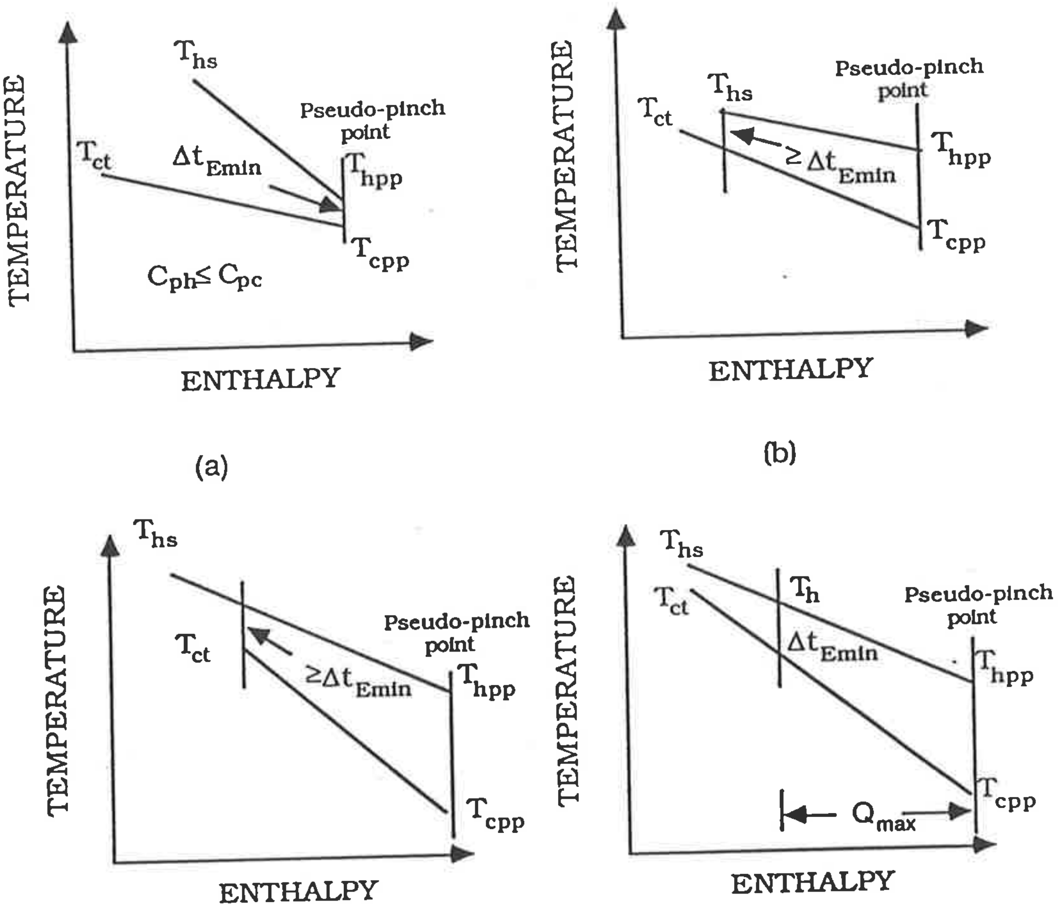
and $T_h < T_{hs}$ and ($T_h - \Delta t_{Emin}$) $< T_{ct}$.

The subscripts hs, hpp, ct and cpp denote the following temperatures- the hot stream starting, the hot stream pseudo-pinch, the cold stream target and the cold stream pseudo-pinch, respectively.

For a 'sink' subproblem, an arrangement of matches not fulfilling the first inequality may necessitate stream splitting. The C_p-Table [91] may be used to identify the matches for which the first inequality is invalid. Provided the remaining feasibility criteria are satisfied then stream splitting will not be required for these matches. Violation of the last two criteria [(b) and (c)] usually indicates that a hot stream will have to be split. Forcing a stream match [condition (d)] may avoid stream splitting.

5.8 Design of Source Subproblem

For 'source' subproblems the feasibility criteria are analogous.



(a) (b)

(c) (d)

Figure 5.14: Temperature feasibility for stream matching immediately adjacent to the pseudo-pinch point for 'sink' subproblem

5.8.1 Stream Population at the Pseudo-Pinch

```
SOURCE PROBLEM
START
If $N_h \leq N_c$
split a hot stream
place the matches
try removing the split stream later.
```

OR

```
SOURCE PROBLEM
START
If $N_h \leq N_c$
place pseudo-pinch matches
match the remaining streams without violating $\Delta t_{Emin}$ constraint
Are all streams at the pseudo-pinch satisfied ?
if not usually split a hot stream and go to start
```

5.8.2 Temperature feasibility criteria

For the source subproblem,

$$Q_h = C_{ph}(T_{hpp} - T_{ht})$$

$$Q_c = C_{pc}(T_{cpp} - T_{cs})$$

The conditions to be satisfied can be defined in a similar manner to sink subproblems (refer Figure 5.15) and are as follows:

(a) $C_{ph} \geq C_{pc}$; $Q_{max} = min(Q_h, Q_c)$

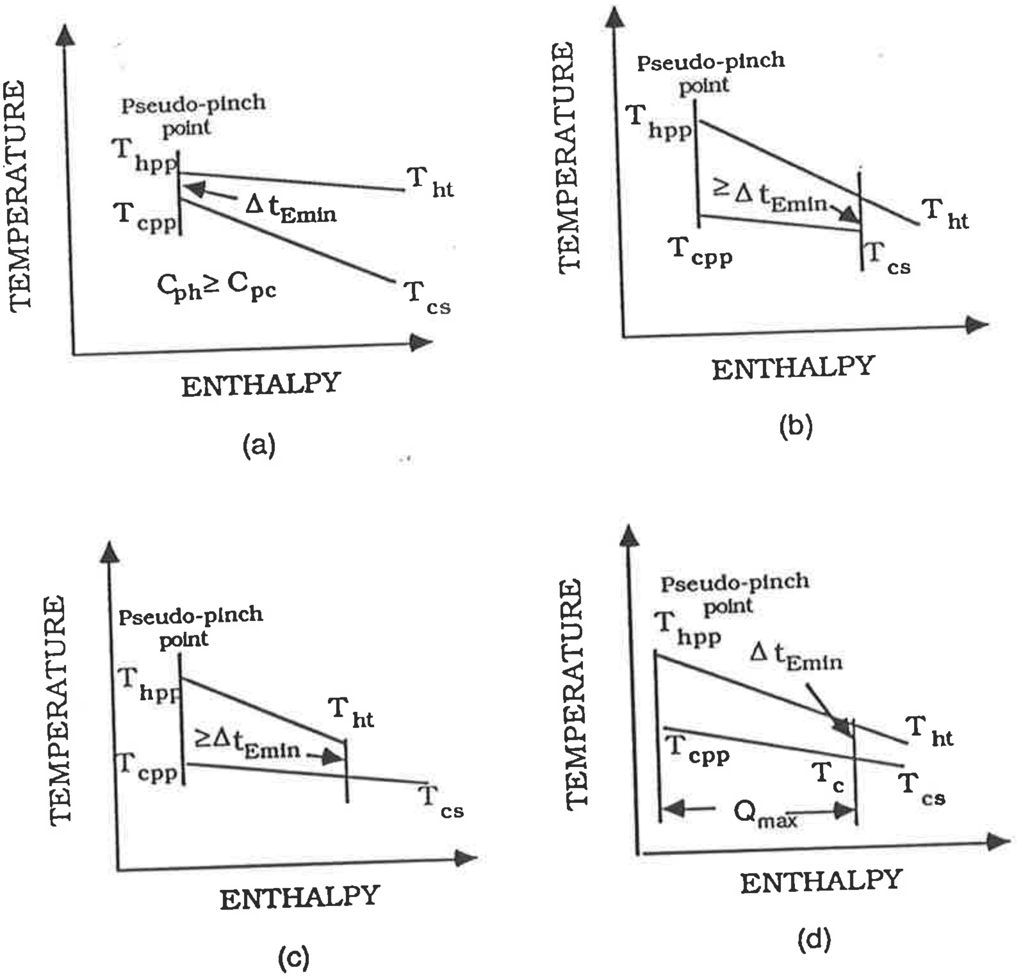


Figure 5.15: Temperature feasibility for stream matching immediately adjacent to the pseudo-pinch for 'source' problem

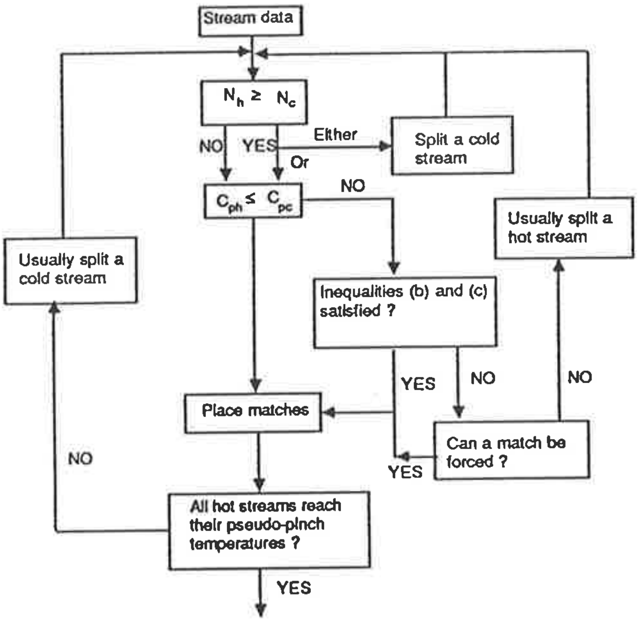


Figure 5.16: Above pseudo-pinch design algorithm

(b) $Q_{max} = Q_c \leq Q_h \leq C_{ph}(T_{hpp} - \Delta t_{Emin} - T_{cs})$

(c) $Q_{max} = Q_h \leq Q_c \geq C_{pc}(T_{cpp} + \Delta t_{Emin} - T_{ht})$

(d) $Q_{max} \leq Q_c \leq Q_h = C_c(T_{ccp} - T_c)$

where

$$T_c = \frac{C_{ph}(T_{hpp} - \Delta t_{Emin}) - (C_{pc}T_{cpp})}{(C_{ph} - C_{pc})}$$

and $T_c > T_{cs}$ and ($T_c + \Delta t_{Emin}$) $> T_{ht}$

the subscripts cs, ht identify the temperatures of the cold stream starting and the hot stream target,respectively.

The complete design procedure is summarized in Figure 5.16 and Figure 5.17.

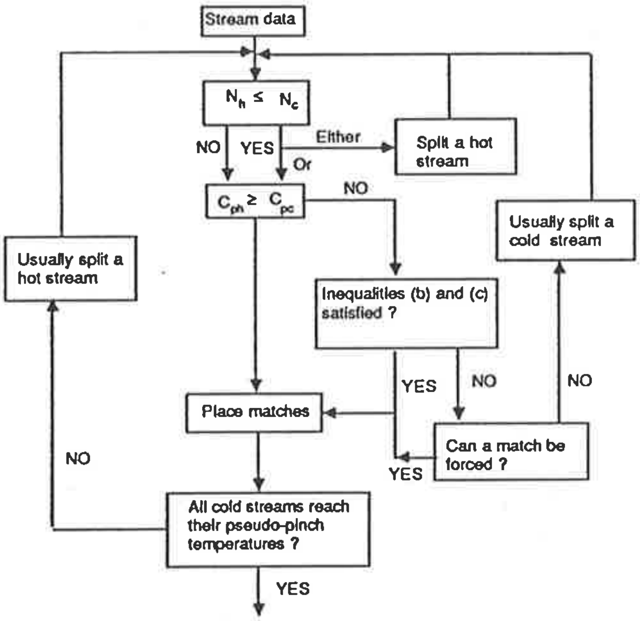


Figure 5.17: Below pseudo-pinch design algorithm

5.9 Design of the Remaining Network

Once the pseudo-pinch matches are placed, the remaining problem can be designed employing the above mentioned rules depending on the subproblem. It should be noted that the remaining problem is still in enthalpy balance and only requires either hot or cold utility depending on the subproblem. The utilities can be placed at appropriate temperature level. The above outlined rules can also be employed in selecting the non-pinch matches when the pinch design method is employed.

5.10 Summary of the Pseudo-Pinch Design Procedure

1. For the given problem, the value of α (the additional utility requirement) is allocated by the designer.

2. The pseudo-pinch temperatures are fixed according to the heuristics based on the knowledge of process conditions. This step also divides the problem into only two separate subproblems.

3. The design commences at the pseudo-pinch and develops by moving away from the pseudo-pinch. Options regarding stream splitting and matching are identified using the feasibility criteria have been outlined. These criteria ensure that the "ticking-off" heuristic is used.

4. Should the designer wish to force a match, its maximum heat load can be calculated using the formulae outlined.

5. The remainder of the network may be completed by appropriately applying the rules for the sink and source subproblems.

5.11 Examples

The method will be demonstrated by designing the networks for two simple problems. The first example illustrates the simplicity of the method for generating a network. The second example illustrates the flexibility available to a designer when employing the proposed design method and demonstrates the ease with which alternate topologies can be generated.

5.11.1 Example 5.3

Problem TC2, previously solved by Colbert [25] is used as an example for comparison purposes. The data for the problem is summarized in Table 5.4. The values of Δt_{Nmin} and Δt_{Emin} are 16.67 K and 3.33 K respectively. The energy targets for these Δt values are 80 kW and 40 kW respectively. Hence, the value of α is 40 kW. The pinch point is determined by the entrance of hot stream 2 at 150°C. Thus, the pseudo-pinch temperature of all the cold streams is fixed at 146.7°C [150 - 3.33]. Hot stream 1 is responsible for the heat transfer across the pinch. Hence, all the heat

Table 5.4: Data for example 5.3 [25]

$\Delta t_{Nmin} = 16.67$ K and $\Delta t_{Emin} = 3.33$ K

Stream Number	C_p(kW/K)	T_s(°C)	T_t(°C)
1	180	40	2
2	150	40	4
3	60	180	3
4	30	130	2.6

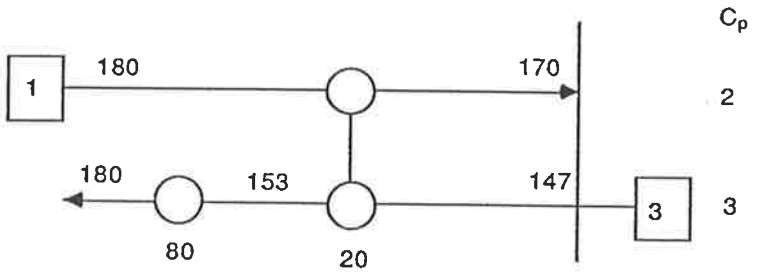
leakage across the pinch will be associated with this stream. Thus, the pseudo-pinch temperature of this stream will be 170°C [150 + 40/2].

5.11.2 Above Pseudo-Pinch Design of Example 5.3

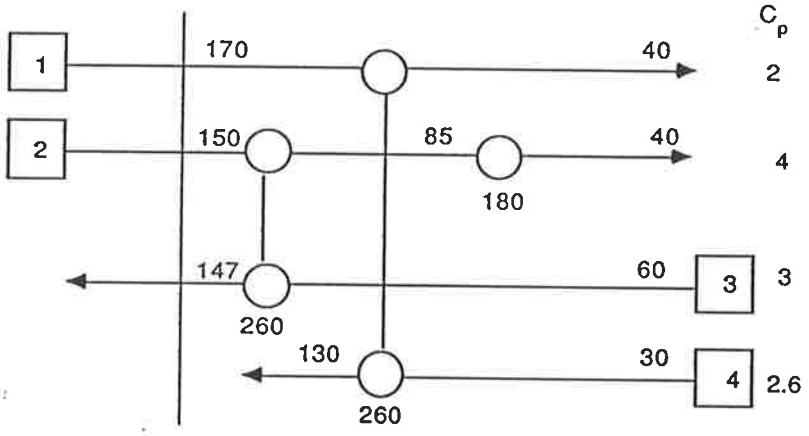
There are only two streams in the subproblem and for these two streams the inequality $C_{ph} \leq C_{pc}$ is valid. The resulting network is shown in Figure 5.18. The hot utility requirement is identical to the target, viz. 80 kW.

5.11.3 Below Pseudo-Pinch Design of Example 5.3

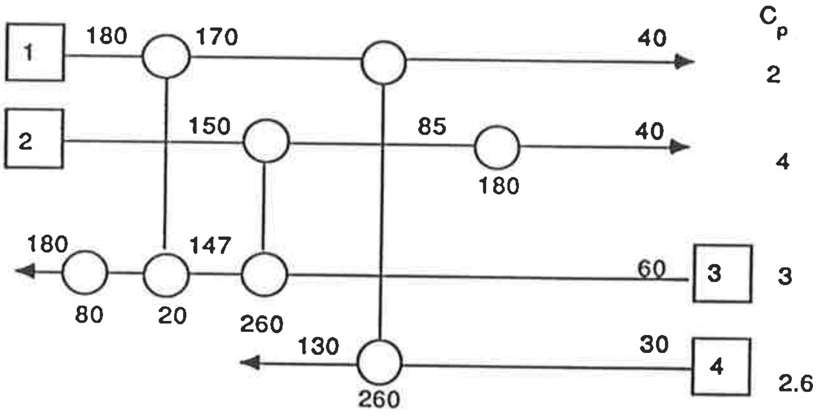
Here there are two hot streams and two cold streams. So, the stream feasibility criteria are satisfied. However, although for a 'real' pinch situation stream splitting is necessary, here as the feasibility criteria (b) below pseudo-pinch is satisfied for a match between the hot stream 1 and the cold stream 4, stream splitting is unnecessary. Placing the pseudo-pinch matches results in a subset equality, reducing the U_{min} source to three units. Again, the cold utility requirement meets the utility



a: Above pseudo-pinch design



b: Below pseudo-pinch design



c: Final design

$\Delta t_{Nmin} = 17$ K, $\Delta t_{Emin} = 3.3$ K.

Relative cost = 115.14.

Figure 5.18: A network for example 5.3

target. The design is illustrated in Figure 5.18.

The final design is obtained on merging the above and below pseudo-pinch designs as detailed in Figure 5.18. An identical design was also reported by Colbert [25]. By way of comparison, his solution to the problem required subdivision into six subnetworks. The initial design had an energy consumption greater than the target, necessitating the merging of heaters and coolers and contained 12 units thus requiring intra-subnetwork matching and subsequent inter-subnetwork matching. Furthermore, he has also reported that in other examples troublesome subnetworks will have to be identified and overcome using the troubleshooting table of Su [141]. The initial network is simplified by breaking loops and merging units. In short, a number of complex steps is required to generate the final design. Using the pseudo-pinch design approach, these complexities disappear and only minor changes are needed to the initial design. Using Colbert's algorithm for more complex problems, a sophisticated computer program would be required and the identification of all possible topologies can be a difficult task.

To illustrate the efficient generation of alternative networks using the pseudo-pinch method consider the following example.

5.11.4 Example 5.1

The data for this problem is presented in Table 5.3. A final topology obtained by employing the pinch design method is illustrated in Figure 5.6. The initial MER design for $\triangle t_{Emin} =$ 20 K was simplified using the energy relaxation procedure outlined in the previous chapter. For the given conditions of $\triangle t_{Emin} =$ 20K, the pinch point is determined by the entrance of cold stream 4. Hence, the pseudo-pinch temperature for the hot streams 1 and 2 is 140°C and for the cold stream 4 is 120°C. As the energy consumed by the final network corresponds to a value of $\triangle t_{Nmin} =$ 32 K, α = 900 kW. This additional heat load is carried by stream 3 and hence the pseudo-pinch temperature of cold stream 3 would be 97.5°C.

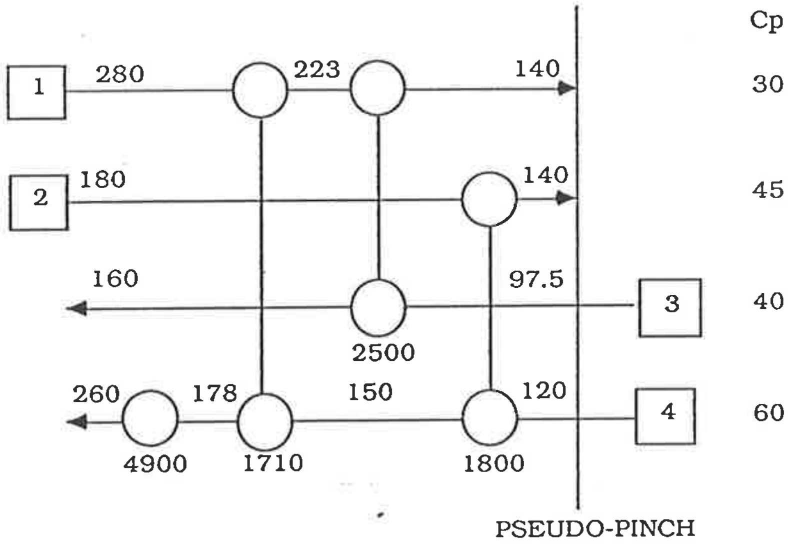


Figure 5.19: Above pseudo-pinch design 1 of example 5.1

5.11.5 Above Pseudo-Pinch Design of Example 5.1

The two possible designs are illustrated in Figure 5.19 and Figure 5.20. It is interesting to note that the topology of Figure 5.20 would not have been identified if the pinch design method were employed.

5.11.6 Below Pseudo-Pinch Design of Example 5.1

Again, two designs are possible as illustrated in Figure 5.21 and Figure 5.22. The matches suggested in Figure 5.21 would not be identified by the use of the pinch design rules.

The above and below pseudo-pinch designs can be combined to create four different fixed energy designs as illustrated in Figure 5.23(a) to (d). These networks will

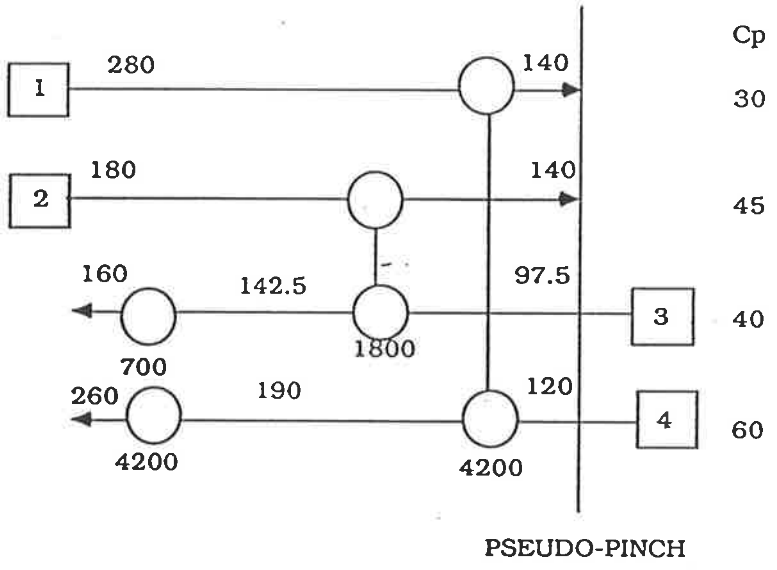


Figure 5.20: Above pseudo-pinch design 2 of example 5.1

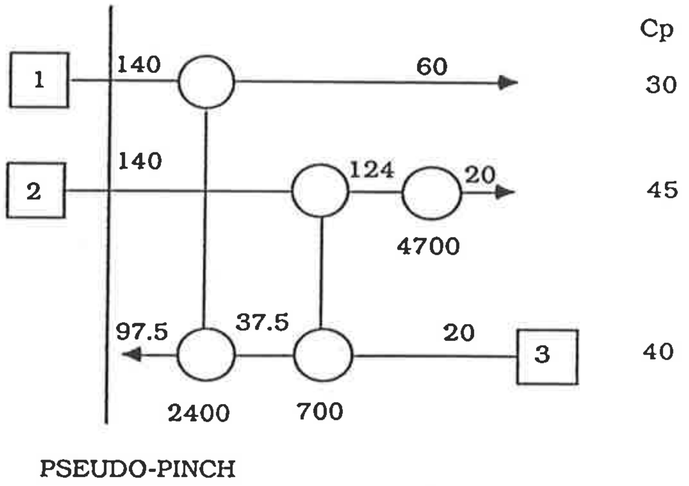


Figure 5.21: Below pseudo-pinch design 1 for example 5.1

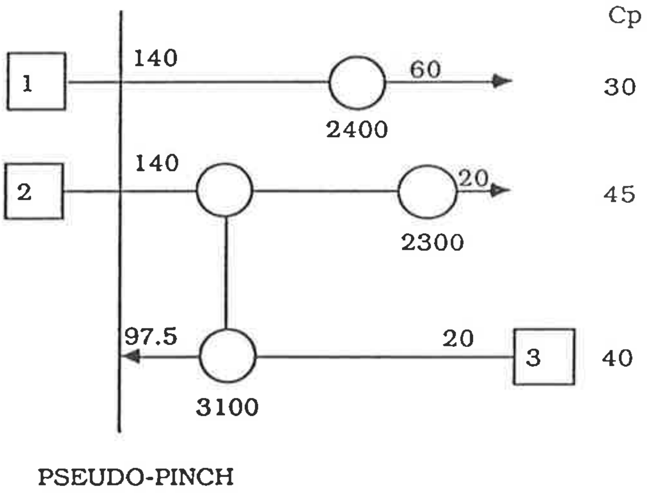


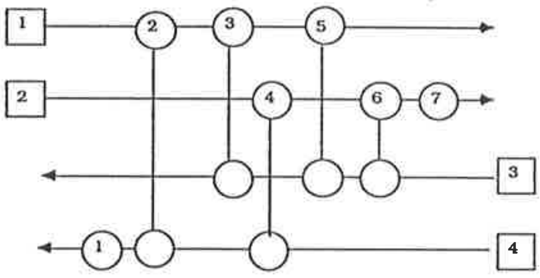
Figure 5.22: Below pseudo-pinch design 2 for example 5.1

be simplified later. Even very complex problems featuring different topologies can be rapidly generated by hand calculations and such an example using the outlined algorithm is illustrated in Figure 4.21 in the previous chapter.

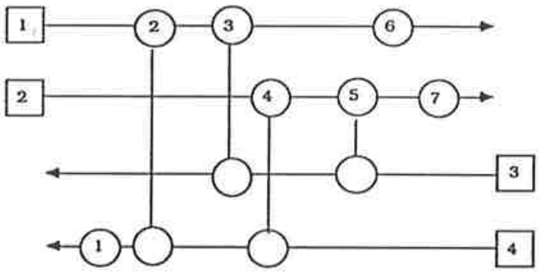
5.12 Simplifying the Fixed Energy Design

5.12.1 Removal of Stream Splits

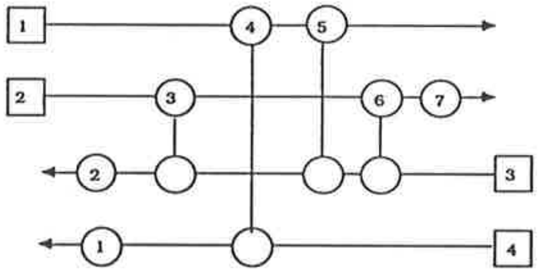
Although stream splits can reduce total area requirements, they are normally avoided as a network featuring them often proves difficult to control. Furthermore, the piping cost of the network will also increase. By not utilizing the pseudo-pinch design method, the designer may decide to split a stream at the pseudo-pinch point without checking the feasibility of a topology of the type shown in Figure 5.13.



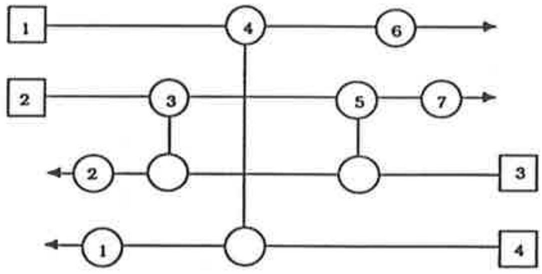
(a): Topology 1 for example 5.3.
Relative cost = 235.0



(b): Topology 2 for example 5.3.
Relative cost = 223.0



(c): Topology 3 for example 5.3.
Relative cost = 244.4



(d): Topology 4 for example 5.3.
Relative cost = 233.7

Figure 5.23: Different network topologies for example 5.1

Once an initial topology is devised, a linear program can be formulated for the total network to minimize the total energy consumption (i.e. maximize energy recovery). The solution to this problem may be used to determine the necessity of stream splitting. If a solution to the LP exists with the minimum energy consumption equal to the already specified value, then this solution is the unsplit design. However, an infeasible solution (i.e. the minimum energy requirement calculated by solving the LP is not equal to the desired energy consumption) indicates that stream splits are unavoidable at that energy level. Splitting may still be avoided by forcing stream matches at the pseudo-pinch point or by incurring an energy penalty or by repeated matches as in typical crude oil preheat trains [24,25].

5.12.2 LP Formulation

Objective Function

$$min\ EC_{\Delta t_{Nmin}} = min\ Q_h + Q_c \tag{5.6}$$

Constraints

1. Equality Constraints:
   (a) Enthalpy balance over all matches for an individual stream:

$$\sum_{j=1}^{N_{cold}} \sum_{k=1}^{N_{unit}} Q_{ijk} = Q_i \qquad i = 1 \ldots N_{hot} \tag{5.7}$$

$$\sum_{i=1}^{N_{hot}} \sum_{k=1}^{N_{unit}} Q_{ijk} = Q_j \qquad j = 1 \ldots N_{cold} \tag{5.8}$$

(b) Enthalpy balance for streams in an exchanger.(For $k = 1 \ldots N_{units}$)

$$C_{pi}(T_{ik,in} - T_{ik,out}) = Q_{ijk} \quad i = 1 \ldots N_{hot} \tag{5.9}$$

$$C_{pj}(T_{jk,out} - T_{jk,in}) = Q_{ijk} \quad j = 1 \ldots N_{cold} \tag{5.10}$$

2. Inequality Constraints:

(a) Δt_{Emin} constraints on each unit[1].

$$T_{ik,in} - T_{jk,out} \geq \Delta t_{Emin} \tag{5.11}$$

$$T_{ik,out} - T_{jk,in} \geq \Delta t_{Emin} \tag{5.12}$$

$$\tag{5.13}$$

for $i = 1 \ldots N_{hot}, j = 1 \ldots N_{cold}$, and $k = 1 \ldots N_{unit}$.

5.12.3 Decreasing the Number of Units

The target minimum number of units that a network can have is given by equation(2.3) The total number of units in an initial FER (fixed energy recovery) design will be

$$U_{min_{FER}} = U_{min_{sink}} + U_{min_{source}}$$

$$U_{min} \leq U_{min_{FER}}$$

This inequality indicates the presence of loops in the network. The previous chapter analysed the problem of loop breaking and energy relaxation in 'real' pinch MER networks and a loop network interaction algorithm (called LONITA) was proposed.

---

[1] This formulation implies units solely employing counter - current flow

The algorithm can be invoked here to identify the possible exchangers to be eliminated. It can also be used for identification of constraints for loop breaking. Since energy consumption is not relaxed, a systematic search may have to be conducted in order to identify the optimal network. For the proposed method the definitions of the different key exchanger types are modified and given below:

Type A:

Such a unit is located on a stream entering the network and has a temperature difference equal to $\triangle t_{Emin}$. Such units will often be found immediately adjacent to the pseudo-pinch and their loads can only be decreased.

Type B:

This unit is necessary in the network for one of the streams in this match to achieve its target temperature. Therefore, the heat load of unit of type B may be either increased or decreased but the unit cannot be eliminated.

Type C:

During the loop-breaking process, Type C units may not be able to absorb the available load without violating the $\triangle t_{Emin}$ constraints. Hence, identification of type C units will dictate the amount of heat load that can be shifted around the loop. This is very important as the heat-load shifting can result in changes in the number of shells and the total network area without decreasing the number of units.

With the units in a loop so identified, the designer can then investigate all the possible options or based on experience and screen the alternatives in order to discard the unattractive ones.

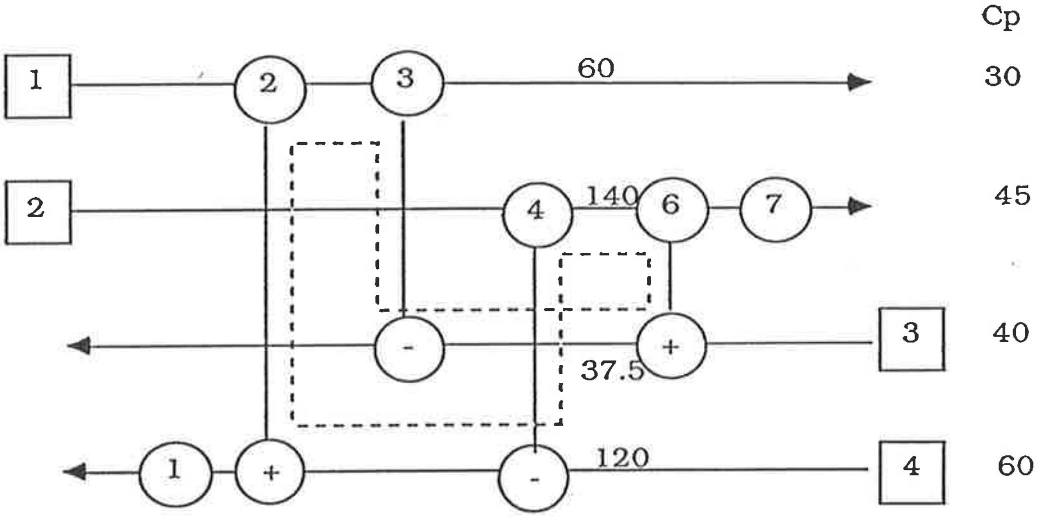


Figure 5.24: LONITA applied to topology 1 of example 5.1 [$\Delta t_{Emin} = 20$K]

5.12.4 Illustration of Loop-Breaking Algorithm

Consider the network previously developed and shown in Figure 5.23a. Units 3 and 5 can be merged. A second level loop (2,3,6,4) can be easily identified in Figure 5.24. Unit 4 is of Type A and so the load on this unit should decrease. Allocation of the '+' and '-' signs to the units shows that unit 3 is the only additional unit whose heat load should be decreased. However, unit 3 cannot be removed as it is of Type B and is necessary for stream 1 to reach its target temperature. Thus, the only candidate for removal is unit 4. However, unit 6 is of Type C and can have an additional heat load of only 100 kW [(40 - 37.5)×40]. So in the network the loop cannot be broken, but a load of maximum 100 kW can be transferred around the loop and its effect on the number of shells and the total cost of the network can be investigated. Figure 5.23(b) and Figure 5.23(d) can be simplified to the network shown in Figure 5.6. The final network obtained by applying LONITA to

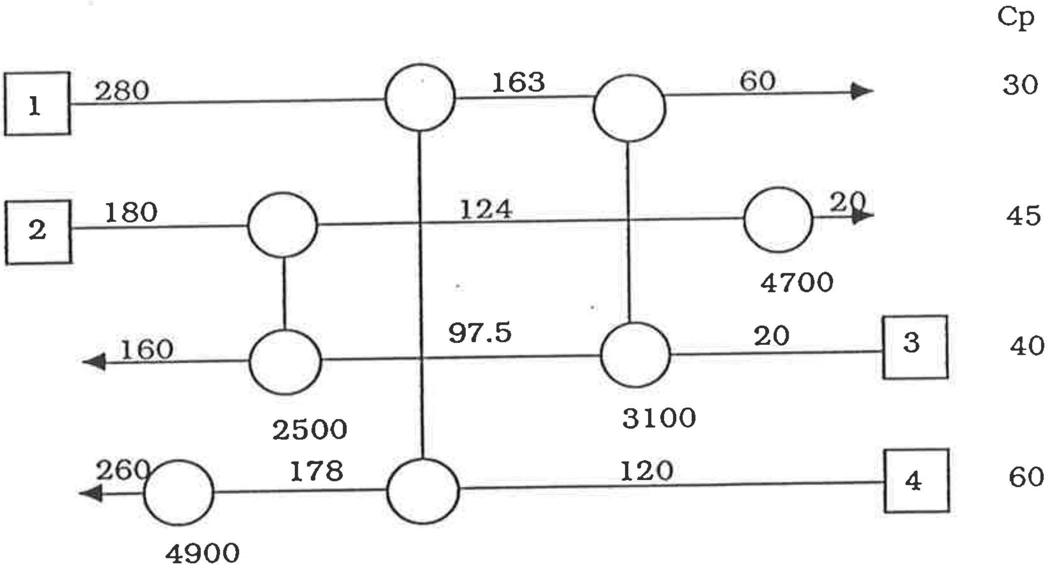


Figure 5.25: Design 3 for example 5.1

Figure 5.23(c) is illustrated in Figure 5.25.

Thus, by employing systematic analysis, three different topologies have been easily identified using hand calculations. It should also be noted that the method is simple in concept and the designer retains complete control of the evolution as all the possible options are quickly and easily identified. These can then be screened on the basis of the total capital cost using the equations presented earlier or by employing 'in-house' cost estimation procedures. Operability analysis can now be performed on the promising designs to select the final network.

Table 5.5: Costs and Topology Changes - problem TC2 ($\triangle t_{Nmin} = 50$ K, 20 K)

$\triangle t_{Nmin} = 50$ K

$\triangle t_{Emin}$	Stream splits	Units	Shells	Area	Capital Cost	Energy Cost	Total Cost
20	-	5	8	47.12	61170	15585	21700
25	-	6	8	42.14	59090	15585	21490
30	-	6	7	43.51	58790	15585	21460
35	-	6	7	43.48	58770	15585	**21460**
40	-	7	8	43.08	62920	15585	21880
45	-	8	9	41.39	70200	15585	22610
50	2	8	9	42.16	73980	15585	22980

$\triangle t_{Nmin} = 20$K

6.67	-	5	14	86.8	101060	5925	**16030**
10	-	7	14	79.3	103390	5925	16260
10	2	6	18	108	131410	5925	19070
15	2	7	17	84.2	118940	5925	17820
20	-	7	16	75.6	114330	5925	17360

5.13 Network Costs & Optimization: Capital- Energy Tradeoff (Influence of $\triangle t_{Nmin}$, $\triangle t_{Emin}$ and Economic Conditions)

The definition of a pseudo-pinch point and the identification of candidate streams capable of 'slipping' across the pinch provides the designer with powerful insights into the capital-energy tradeoff underlying network design and evolution. To illustrate this point, consider Table 5.5 which summarizes the results of cost calculations for the problem (TC2) given in example 5.3 with $\triangle t_{Nmin}$ fixed at 50K and 20K. The cost data is summarized in Appendix A.

From Table 5.5 some interesting observations can be made. Consider the capital cost of the network when Δt_{Nmin} is 50 K. In this case, the pinch design cost is \$ 73980. However, the optimal capital cost network has a $\Delta t_{Emin} =$ 35 K which is 21% lower than the pinch design network, but the total annual cost of the optimal network is only decreased by 7%. Similarly when $\Delta t_{Nmin} =$ 20 K the cost of the optimal network is decreased by 12% and the total annual cost is decreased by 7.6% when compared with the pinch design.

Two designs are possible when the value of Δt_{Nmin} is 20 K and the value of Δt_{Emin} is 10 K. The difference in the capital cost of both the designs is due to the presence of stream splits in one of the designs which subsequently increases the network area and the total number of shells required. Though the split stream design has a lesser number of units its cost is higher which further justifies that a design having near minimum number units and the same energy recovery need not be the optimal design. This is also observed the network when the value of Δt_{Nmin} is 50 K and the value of Δt_{Emin} is 35 K.

The data also clearly illustrates the discontinuities ("kinks") in the cost curve resulting from topology changes. Clearly, the designer need only consider "kink point" designs in the initial phase. This reduces the solution space and consequently the computation load. As well, the prevailing economic conditions (i.e the relative costs of capital and energy) will strongly influence the network topology and the different optimal network structures in differing economic situations are readily screened.

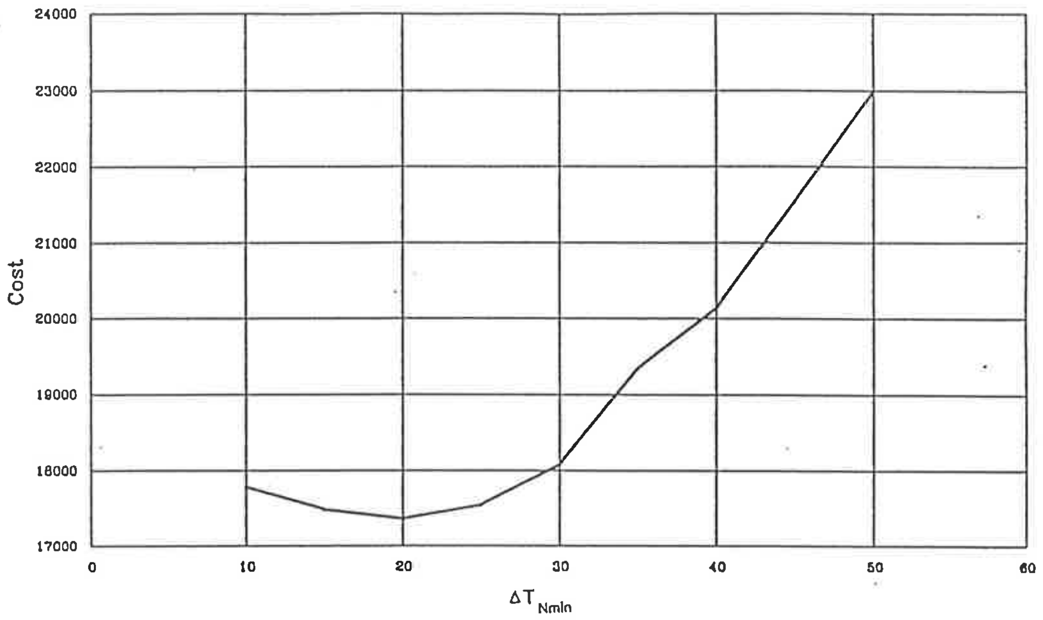
Schematic cost curves illustrating the effects of variation of both Δt_{Emin} and Δt_{Nmin} for one such set of economic conditions are presented as Figure 5.26. It can be seen that the cost curves are not monotonic and do not follow any general trend. As a result of ' topology traps ' [3] noted in the previous chapter, the selection of the initial starting point is critical to the location of the global optimum. For this example, the global optimum occurs at the combination of $\Delta t_{Nmin} =$ 25 K and $\Delta t_{Emin} =$ 9.33 K

Table 5.6: Comparison of Total Costs - Pinch design and Optimal Design

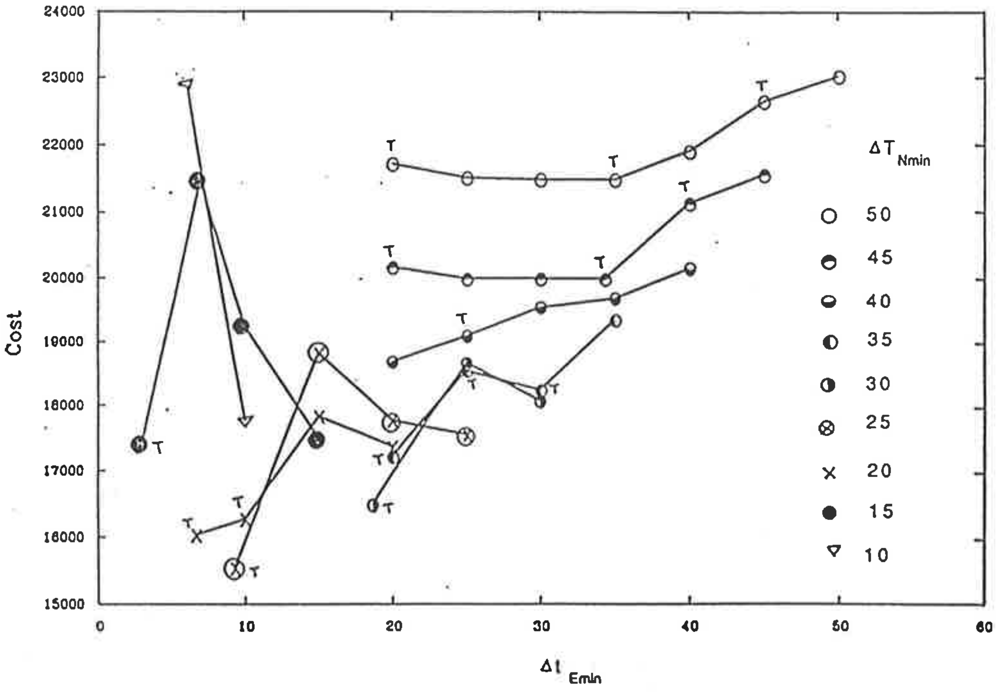
Δt_{Nmin} K	Total Cost (Pinch Network)	Δt_{Emin} K	Total Cost (Optimal Network)
50	22980	35	21460
45	21530	34.33	19980
40	20120	20	18680
35	19326	20	17200
30	18060	18.66	16490
25	17540	9.33	**15530**
20	17360	6.67	16030
15	17480	3	17410
10	17770	10	17770

(Table 5.6). In the above example, for $\Delta t_{Nmin} =$ 20 K, $\Delta t_{Emin} =$ 6.67 K, represents a threshold point for the given energy consumption, as below which a minimum unit design is always possible. The threshold value for Δt_{Emin} is dependent upon Δt_{Nmin} .

Again another interesting observation can be made from Table 5.6. Here the pinch design for $\Delta t_{Nmin} =$ 10 K is the optimal design. This is because as the value of Δt_{Emin} is decreased, the number of shells increase without any decrease in the number of stream splits as well as the number of units which results in an increase in the total network cost.



(a) Cost curves for $\Delta T_{Nmin} = \Delta t_{Emin}$ (MER Design)



T - Change In topology

(b) Cost curves for fixed energy consumption

Figure 5.26: Typical cost versus exchanger approach Δt curves

Table 5.7: Comparison of Optimal Designs based on Topology

Design Method	Units	Shells	Area	S tream splits
Pinch Design Method Design I (Figure 4.20)	18	24	6.33	1
Pseudo-Pinch Method Design II (Figure 5.27)	13	23	6.65	0

5.14 Comparison of Optimal Designs

Figure 4.20 illustrates a globally optimal design reported by Ahmad and Linnhoff [2]. This network was obtained using the pinch design method. The capital cost was calculated by the following co-relation:

$$\text{Installed unit cost (\$)} = 700\ \mathrm{A}^{0.83}(m^2)$$

An alternative network featuring the same energy consumption is illustrated in Figure 5.27 which is obtained by the design method reported in this chapter. Table 5.7 compares both the designs. The network obtained by employing the pseudo-pinch design method has less units and shells. Futhermore, it has no stream splits. Due to these reasons, it is a simple design and is likely to have good operability characteristics. However, it has a slightly greater area (0.32 m^2).

Table 5.8 compares the capital cost of both the topologies for different cost equations. These figures clearly indicate that designs obtained by the method reported in this chapter have a distinctly comparable costs. Furthermore, the simple network topologies are obtained and so are good candidates for further investigation based on operability.

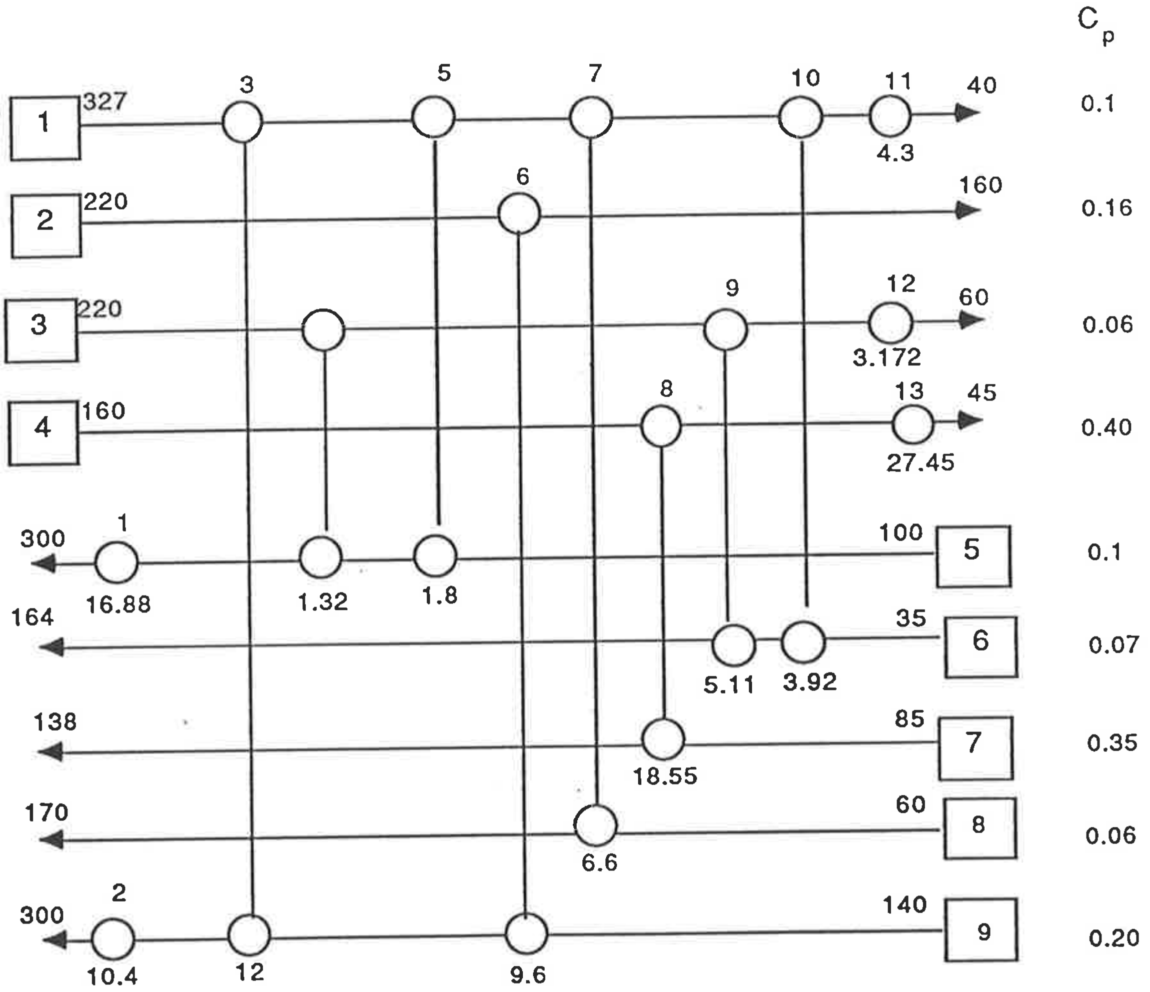


Figure 5.27: An alternative design to Ahmad and Linnhoff's problem

Table 5.8: Cost Comparison of Optimal Design

Cost Equation	Pinch Design Method Design I (Figure 4.20)	Pseudo-Pinch Method Design II (Figure 5.27)	Design II as a % of Design I
$700A_u^{0.83}$	4650	4515	97
$700A_s^{0.83}$	5300	5544	104
Eq(E.8)[1]	89310	84020	94

1. Cost parameters reported in Appendix A

5.15 Conclusions

A simple, new design algorithm is presented. It incorporates the clear specification of two approach temperatures (network and individual exchanger Δt_{min}) and additional utility consumption α prior to design. The method, by employing the concept of a pseudo-pinch with subsequent allocation of excess utility α, enables the designer to rapidly generate (normally by hand calculation) a large set of promising topologies for the network. It also displays considerable promise for extension to multiple-pinch situations, integration of utility and power systems and to retrofitting problems.

Chapter 6

Synthesis of Heat Exchanger Networks With Designer Imposed Constraints

6.1 Introduction

The pinch design method [91] employs the concept of a pinch point to synthesize unconstrained networks. It utilizes the following three principles for generating MER networks:

- Don't use cold utility above the pinch point.
- Don't use hot utility below the pinch point.
- Don't transfer heat across the pinch point for maximum heat recovery.

Using the above principles, unconstrained networks can be easily generated. However, the designer may desire to impose constraints resulting from a variety of process, mechanical or operating factors. For example, it may be that a match between two streams may be prohibited to maintain process safety, or to avoid incurring excessive piping costs associated with a particular match. Further it may be the case that one may not wish to match streams when both are in the vapour phase. Many other instances of such constraints are possible. When such constraints are imposed, extra hot utility may be required. This implies that additional heat will have to be removed by the cold utility. In other words, contrary to the standard 'pinch' design method, cold utility may be employed above the pinch point and hot utility below the pinch point. The pinch design method cannot be used to generate systematically such constrained networks.

Mathematical-programming algorithms have been used in the past to predict the minimum energy requirements of problems subject to constraints. Cerda et al. [20] have proposed a solution methodology based on a transportation model formulation and a trans-shipment model was proposed by Papoulias and Grossmann [117]. These techniques are effective in setting targets, but they fail to provide detailed insights for design and network generation. To synthesize networks, Cerda and Westerberg [22] have solved the transportation model by employing the *" reverse stepping stone L.P. algorithm "* and Papoulias and Grossmann [117] and Saboo et al. [130] used mixed-integer linear programming methods. These methods, though effective, do not identify all possible solutions when multiple solutions exist. In such cases, it is important to be able to generate a variety of solutions, as for example different network topologies satisfying the same constraints may have extremely different operability characteristics [44].

In this chapter, a new sequential, evolutionary design method is proposed for the synthesis of heat exchanger networks with designer-imposed constraints. The design parameters for generating the network are obtained with conventional algorithms by solving a modified trans-shipment formulation of the transportation linear program. Candidate network topologies can then be easily configured by hand computation and the "best" designs are quickly identified even for large problems. The procedure also identifies problems which may have multiple topologies, characterized by minimum energy consumption as well as minimum number of units.

6.2 Trans-shipment Model Revisited

One of the modifications of the transportation problem which deals with the optimum allocation of resources is the trans-shipment model [54]. Papoulias and Grossmann [117] have used this model for targeting the minimum energy requirements for a given set of constraints. According to this model, heat is transferred from the hot streams to the cold streams through intermediate temperature intervals, set by the thermodynamic constraints, i.e. the minimum exchanger-approach temperature $\triangle t_{Emin}$.

6.2.1 Modified Temperature Intervals

The temperature intervals can be defined in a variety of ways, for example by the rules proposed by Linnhoff and Flower [96], Grimes et al. [42] and Cerda et al. [20] (for a detailed discussion see chapter 2). The first procedure yields approximately twice as many intervals for the same problem when compared with the latter methods. To reduce the number of temperature intervals, it was recommended by Papoulias and Grossmann that the rules laid out by Grimes, and subsequently modified by Cerda, be employed. These rules divide the problem at candidate pinch point temperatures i.e. where the problem is likely to be thermodynamically constrained or at the temperatures where streams enter the network.

Depending on the nature of the problem, when designer-imposed constraints are to be implemented, the unconstrained pinch division may no longer be a relevant factor in the design of constrained maximum energy recovery (CMER) networks. Hence, for constrained match problems locating the pinch point is only useful in rare special cases, viz. when constraints have no effect on the maximum energy recovery.

Table 6.1: Data for example 6.1

$\Delta t_{Emin} = 10$ K

Stream Number	C_p(kW/K)	T_s(°C)	T_t(°C)
h1	1.45	300	140
h2	3.2	280	100
c1	2.65	100	225
c2	4.22	140	250

The constraints placed on matches always involve temperature intervals. In the proposed method these temperature intervals must be included in the L.P. formulation, in addition to the temperature intervals specified by Papoulias and Grossmann. These extra temperature intervals are normally fixed by the target temperatures of the constrained streams. The importance of this division will be discussed later in the detailed design procedure.

To illustrate the modified temperature intervals, let us consider the problem data summarized in Table 6.1 (pinch temperatures = 150°C/140°C). The temperature-interval partitioning of the problem for the unconstrained case is presented in Table 6.2. The hot stream temperature intervals are fixed by adding Δt_{Emin} to the cold stream intervals. The modified temperature intervals assuming a single constraint, namely that stream h2 and stream c1 cannot be matched, are detailed in Table 6.3. The additional temperature interval is set by the target temperature of c1 (225°C).

Table 6.2: Temperature intervals (Unconstrained problem)

$\triangle t_{Emin} = 10$ K

Temperature Interval k	Hot Stream Interval	Cold Stream Interval
1	$-\infty$ to 110	$-\infty$ to 100
2	110 to 150	100 to 140
3	150 to ∞	140 to ∞

Table 6.3: Temperature intervals (Constrained problem)

$\triangle t_{Emin} = 10$ K

Temperature Interval k	Hot Stream Interval	Cold Stream Interval
1	$-\infty$ to 110	$-\infty$ to 100
2	110 to 150	100 to 140
3	150 to 235	140 to 225
3	235 to ∞	225 to ∞

6.3 Model - The Modified Trans-shipment Linear Program

The target data (i.e. minimum utility) required for designing a constrained network is first generated by solution of the trans-shipment model of Papoulias and Grossmann [117], but reformulated to include the additional temperature intervals. The first step is to partition the entire temperature range into a total of K temperature intervals as detailed above. These intervals, labelled in descending order of temperature, are identified by the index k ranging from 1 to K. The trans-shipment model (see Figure 6.1) is summarized below employing the notation introduced by Papoulias and Grossmann.

The following sets are defined in order to identify the location of all streams and utilities relative to the temperature intervals[1]:

$$\begin{aligned} H_k &= \{i|\text{hot stream } i \text{ is present in interval } k\} \\ C_k &= \{j|\text{cold stream } j \text{ is present in interval } k\} \\ S_k &= \{m|\text{hot utility } m \text{ is present in interval } k\} \\ W_k &= \{n|\text{hot utility } n \text{ is present in interval } k\} \end{aligned} \tag{6.1}$$

Let Q_{ik} be the heat load of hot stream i entering temperature interval k. This heat load is given by,

$$Q_{ik} = C_{pi} \times \triangle T_k^i \tag{6.2}$$

where $\triangle T_k^i$ is the temperature change of stream i in interval k. Similarly the heat load Q_{jk} of the cold stream j entering interval k is calculated as

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[1] The nomenclature is limited to this section only.

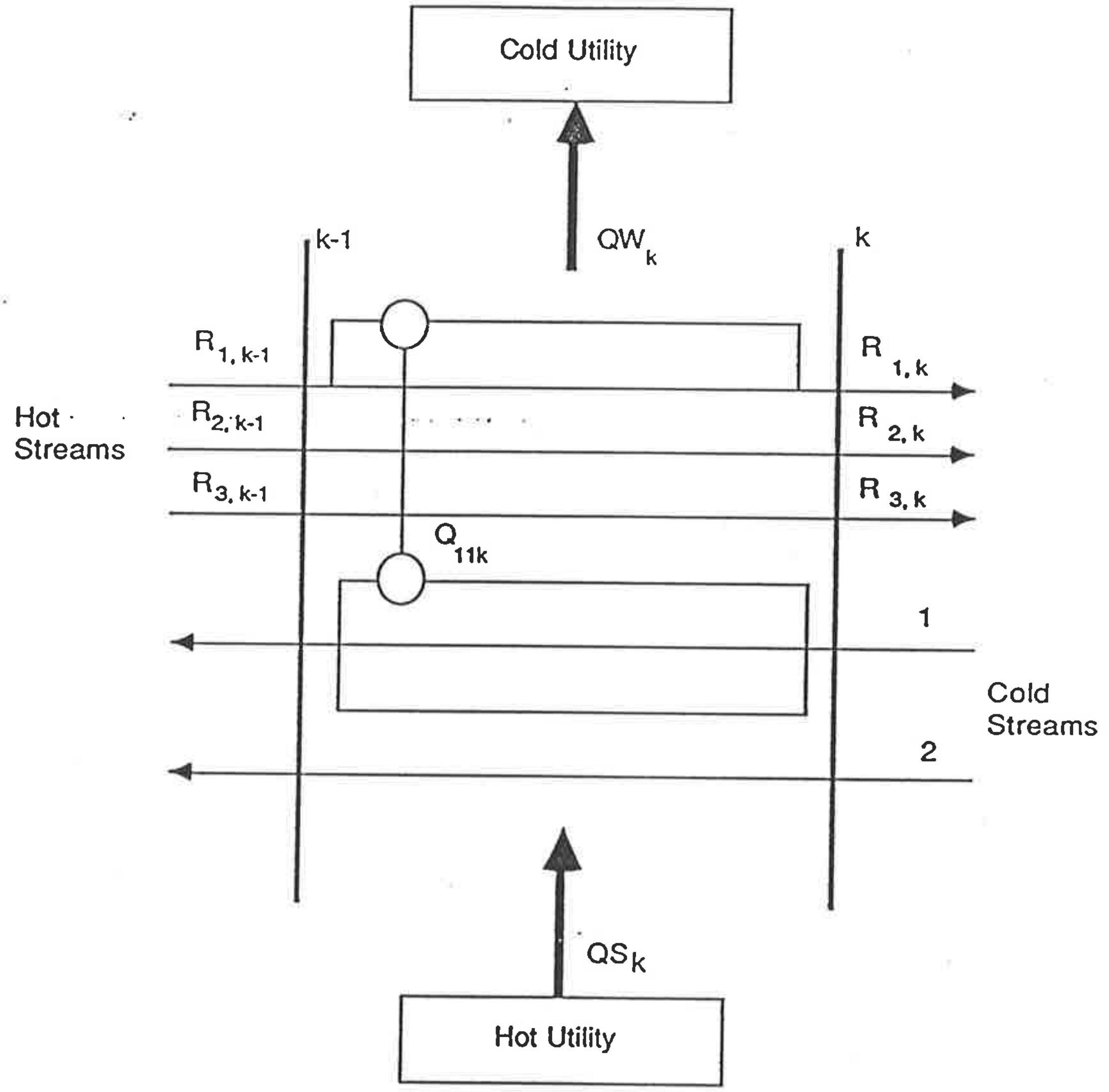


Figure 6.1: The trans-shipment model for energy targeting

$$Q_{jk} = C_{pj} \times \triangle T_k^j \tag{6.3}$$

The heat load of the hot and cold utilities in interval k are Q_{mk} and Q_{nk} respectively. The residual heat flowing out of interval k is R_k. The set of restricted matches is specified for some process streams and is given by

$$RM = \{(i,j) | i \in H,\ j \in C,\ \text{match between } i \text{ and } j \text{ is forbidden } \} \tag{6.4}$$

The set of imposed matches is given by IM

$$IM = \{(i,j) | i \in H,\ j \in C,\ \text{match between } i \text{ and } j \text{ is imposed } \} \tag{6.5}$$

The minimum utility cost problem for restricted matches will be given by the following trans-shipment model:

Objective function:

$$minZ = \sum_k (QS_k + QW_k) = \sum_k [(Q_{ik})_{i=S} + (Q_{jk})_{j=W}] \tag{6.6}$$

Constraints:

Hot stream enthalpy balance:

$$R_{i,k} - R_{i,k-1} + \sum_{j \in C_k} Q_{ijk} = Q_{ik}$$
$$i \in H_k,\ k = 1, ..., K \tag{6.7}$$

Cold stream enthalpy balance:

$$\sum_{i \in H_k} Q_{ijk} = Q_{jk}$$
$$j \in C_k,\ k = 1, \ldots\ldots, K \tag{6.8}$$

Restricted matches:

$$Q_{ijk} = 0$$
$$i, j \in RM \tag{6.9}$$

Imposed matches:

$$Q_{ijk} > 0$$
$$i, j \in IM$$
$$k = 1, \ldots\ldots, K \tag{6.10}$$

Positive heat flows:

$$Q_{ijk} \geq 0$$
$$i, j \in OM$$
$$k = 1, \ldots\ldots, K \tag{6.11}$$

$$R_{i,0} = R_{i,K} = 0 \text{ and } R_{i,k} \geq 0$$
$$k = 1, \ldots\ldots, K - 1 \tag{6.12}$$

The reformulation of the L.P. with the additional temperature interval constraints will give additional output information for the residuals (equation 6.7). It is these residuals which provide the necessary insights for the creation of the sub-problems which lead to a design solution. This development is discussed in the next section.

6.4 Design Procedure

Two types of constraints have to be considered when synthesizing a network:

- Thermodynamic constraint ($\triangle t_{Emin}$, the individual exchanger approach temperature, limit should not be violated)
- Designer imposed match constraints over specified temperature intervals.

A more detailed discussion of the problem is warranted at this stage. Consider the set of composite curves shown in Figure 2.3. Divide this pair of curves into an arbitrary large number of temperature intervals. All the streams in any of these intervals will satisfy the $\triangle t_{Emin}$ constraint. The heat cascade (total residual) associated with these temperature intervals is shown in Figure 6.2(a). The total heat cascaded down (see equation 6.13) from a given temperature interval k is denoted by F_k. For the unconstrained case, the subnetworks in each interval can be designed independently using the TI method proposed by Linnhoff and Flower [96]. But, the design of some of these subnetworks may be unobtainable when designer imposed constraints are considered. As noted before, by employing extra hot and cold utilities, a feasible design for each subnetwork can be achieved. Let α be this minimum additional utility requirement. The same amount of heat will be cascaded down in each subnetwork, as illustrated in Figure 6.2(b). This increase in energy consumption enables the generation of feasible subnetworks obeying the non-thermodynamic constraints. It should be noted that, if the same temperature intervals where used to formulate the trans-shipment model then,

$$\sum_i R_{ik} = F_k + \alpha$$
$$i \in H_k,\ k = 1, 2, ...K \tag{6.13}$$

This analysis suggests that **any partitioning** of the problem for designing the network is acceptable. But, to reduce the design time, the number of subproblems evaluated should be minimal. We propose that the problem should only be subdivided at the candidate pinch points and in addition at the temperatures where the number of constraints changes. The solution of the reformulated trans-shipment model gives information on the stream residuals at these temperature intervals.

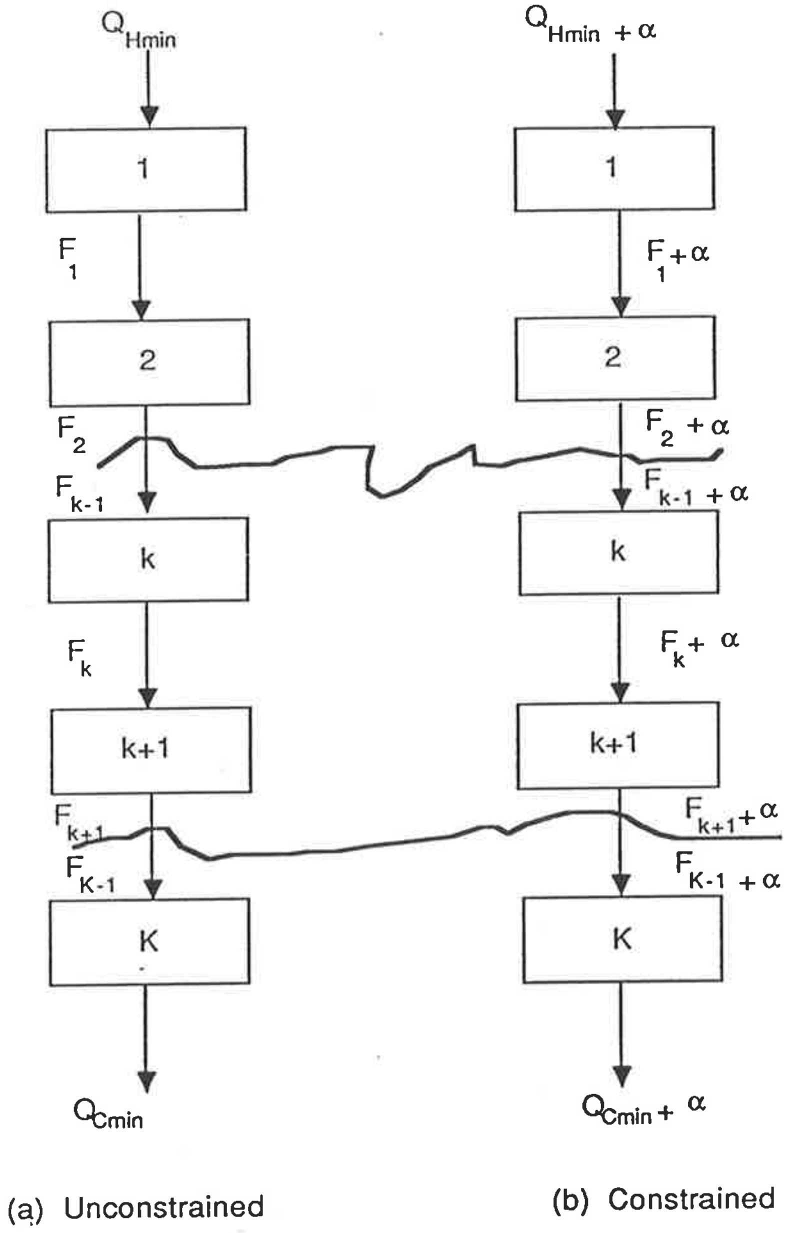


Figure 6.2: Heat cascade

The value of the residuals (R_{ik}) can aid the "correction" of each subproblem so that a feasible design is generated. The correction recommended is to alter the temperature of the hot stream/streams such that the heat that must be passed through any subnetwork is extracted from the coldest part of the hot stream (or streams) above the partition. This is the safest way to allocate it *a priori* since it leaves the hottest heat for integration of the streams above the partition.

The other correction of the subproblem is implemented as the actual design progresses. The hot streams in a subnetwork whose exit temperatures have been modified as mentioned above, will heat all the cold streams to a temperature less than or equal to the subnetwork target temperatures. Hence, if the design of the network is started from the cold end (lowest temperature interval), the temperature to which all the cold streams in this interval are heated can be fixed by placing the actual matches in the subnetwork. These temperatures become the starting temperature of the cold streams in the adjacent higher temperature interval subnetwork. The process is repeated sequentially for all the subnetworks. This procedure is adopted to maintain stream continuity and to keep the design procedure simple and sequential, unlike the pinch design procedure where each subnetwork can be designed independently. Any other method for fixing the cold stream subnetwork starting temperatures may also be used. For example, the heat available from the hot streams can be employed so that the matches are placed at the hot end of the subnetwork. Additional heat would be required at the cold end of the subnetwork. This heat can be obtained from the hot streams in the adjacent higher temperature subnetwork. However, this will result in an increase in the network area due to excessive "criss-crossing" [149] and a subsequent increase in the complexity of the design procedure. Hence, the design is carried out sequentially starting from the cold end of the network.

To illustrate the above procedure, consider the problem 4sp1, data for which is presented in Table 6.4. For the unconstrained problem, the pinch point is located at 249°C/239°C. If we impose the constraint, that a match between the streams h2 and c1 is prohibited [117], then the resulting problem can be further subdivided into a constrained section and an unconstrained section as illustrated in Figure 6.3.

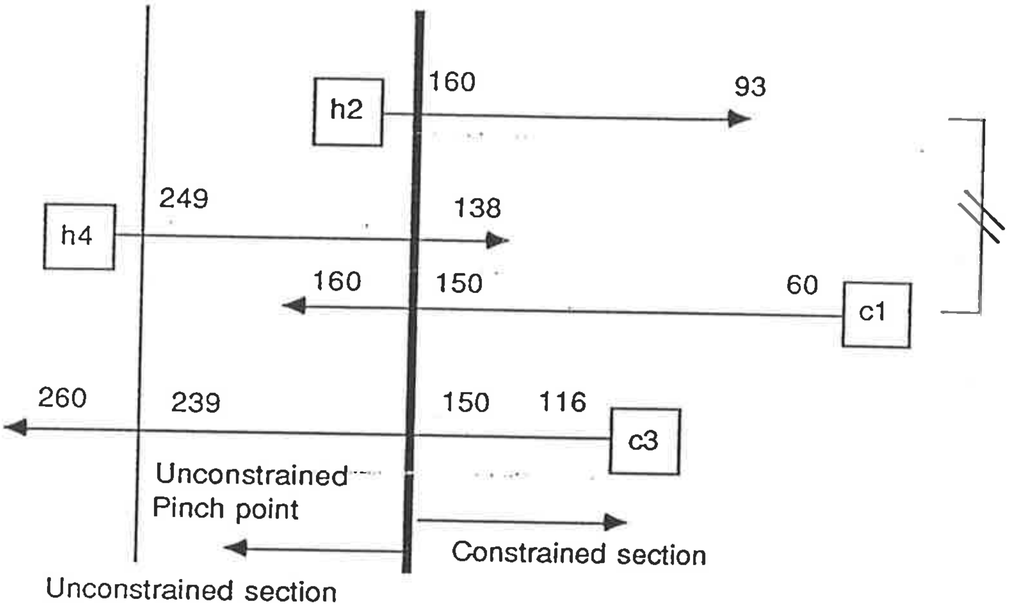


Figure 6.3: Constraint division of the problem 4sp1

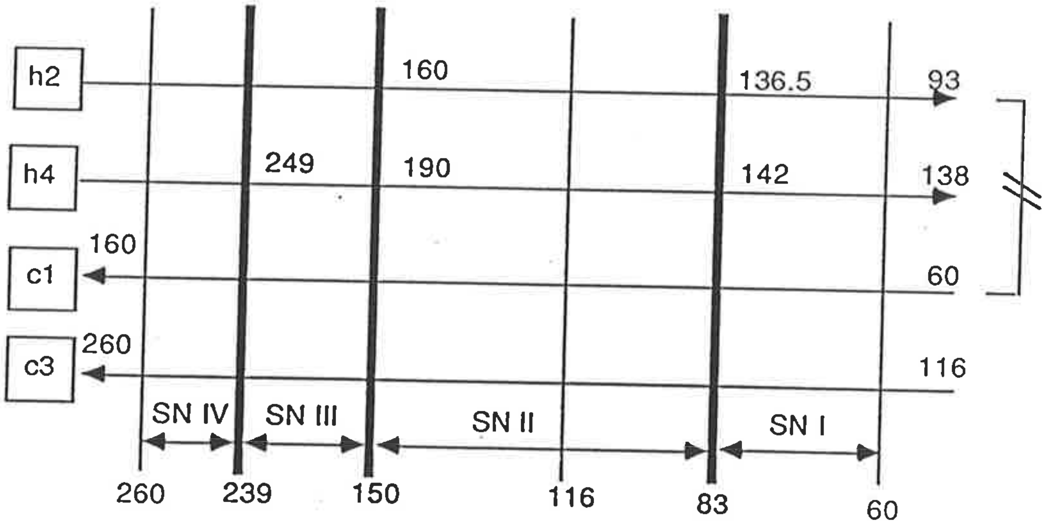


Figure 6.4: Subnetworks for the problem 4sp1 with the modified hot stream temperatures

Table 6.4: Data for problem 4sp1 [81]

$\triangle t_{Emin} = 10$ K

Stream Number	C_p(kW/K)	T_s(°C)	T_t(°C)
c1	7.62	60	160
h2	8.79	160	93
c3	6.08	116	260
c2	10.55	249	138

Table 6.5: Temperature intervals for problem 4sp1

$\triangle t_{Emin} = 10$ K

Temperature Interval k	Hot Stream Interval	Cold Stream Interval
1	$-\infty$ to 93	$-\infty$ to 83
2	93 to 126	83 to 116
3	126 to 160	116 to 150
4	160 to 249	150 to 239
5	249 to ∞	239 to ∞

The temperature intervals for formulating the trans-shipment model are reported in Table 6.5. The constraints are active in the hot stream temperature interval $160°C - 93°C$ and the cold stream temperature interval $150°C - 83°C$. The solution of the trans-shipment model provides the values for the residuals of the hot streams at the constraint division points and is tabulated in Table 6.6. The temperatures of the individual hot streams can be modified so that they actually cascade this residual heat to the lower temperature intervals. For example, stream h4 in this problem has a residual of 321 kW at the constraint point $160°C$. Hence, the stream temperature at this point would be $190.4°C$ $(160° + 321/10.55)$. Furthermore, it should be noted that if all the external heating were to be supplied at the highest temperature, say

Table 6.6: Stream residuals

No.	Temperature	R_{h2}	R_{h4}
1	93	382.1	43.19
2	160	0.0	321.63
3	249*	0.0	0.0

* unconstrained thermodynamic pinch point

270°C, then the pinch point ceases to exist. However, if the hot utility requirement corresponding to that required for the unconstrained problem was supplied at a temperature of 270°C and the additional requirement for the constrained case was supplied at say 160°C, then the problem would still have to be divided at the pinch point.

Assuming all the hot utility is supplied at 270°C, the problem can now be subdivided into unconstrained and constrained subnetworks as illustrated in Figure 6.4. The subnetworks are delineated by the heavy lines and the modified temperatures are also illustrated in the diagram. The problem is not divided at 126/116°C as the unconstrained problem is not pinched at this point. There are four subnetworks to be designed. These subnetworks are not in an enthalpy balance, as is the case with pinch division [91] i.e. heaters may have to be used below the unconstrained pinch point (249/239°C). This also supports the fact that the design of the individual sub-networks will be interdependent and the design procedure must be carried out sequentially.

The design of the network commences at the cold end. Subnetwork I has three streams; h2 has to be cooled from 136.5°C to 93°C, h4 has to be cooled from 142°C to 138°C, and c1 has to be heated from 60°C to 83°C. As the exit temperature of c1 cannot be predicted before this subnetwork is designed, an upper bound of 83°C is

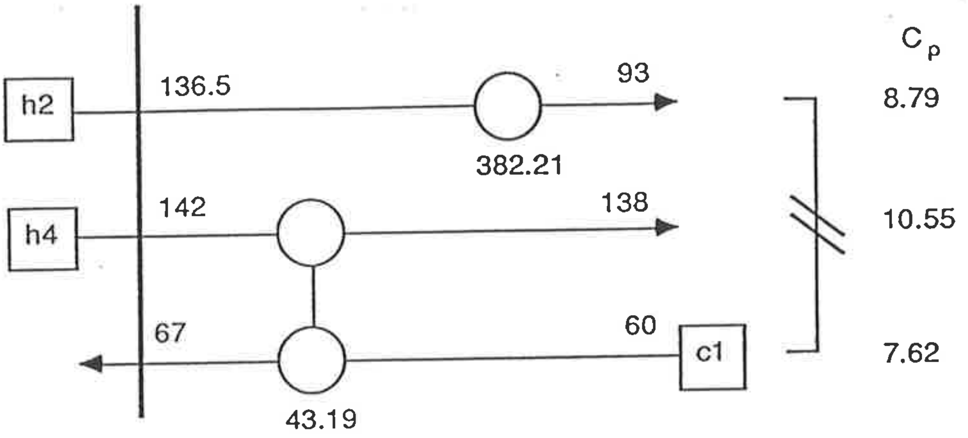


Figure 6.5: Constrained subnetwork I

fixed. The only legal process-process match possible in this subnetwork is between stream h4 and c1. The heat duty of this match is 43.19kW (Figure 6.5). This increases the temperature of c1 to 67°C, ticking-off stream h4 [91] in subnetwork I. Stream h2 has no other process stream available for heat transfer except the cold utility. A cooler of heat duty 328.21 kW is placed on this stream. This cooler duty corresponds to the minimum energy requirement under the imposed constraints.

There are two possible approaches to deal with stream c1:

- Place a heater on this stream to increase its temperature to 83°C.
- Design subnetwork II with stream c1 starting at 67°C instead of 83°C.

The first option will degrade heat by incurring a large exergy loss and hence will not be pursued. It is assumed for convenience that the hot utility will only be used

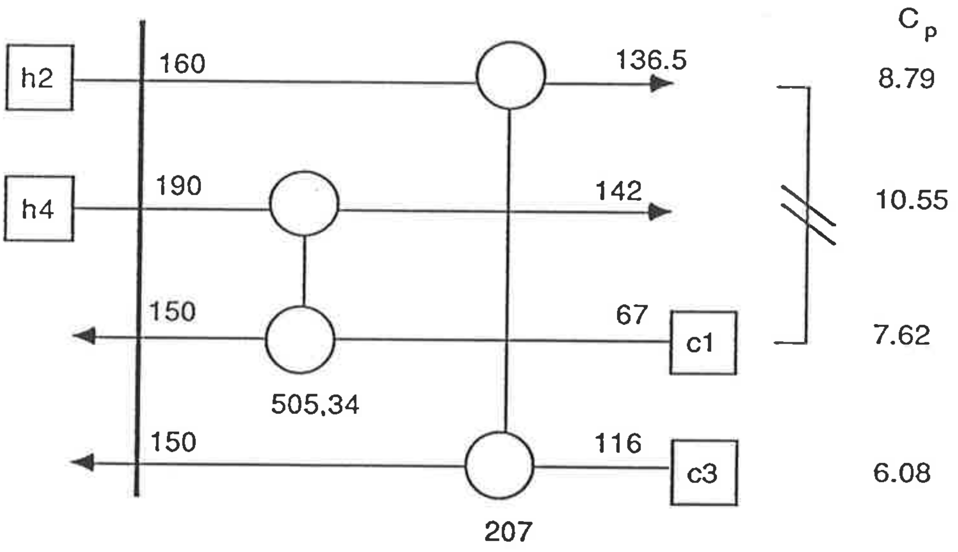


Figure 6.6: Constrained subnetwork II

at the highest temperature required.

Subnetwork II has four streams: h2 has to be cooled from 160°C to 136.5°C, h4 has to be cooled from 190°C to 142°C, c1 has to be heated from 60°C to 150°C, and c4 has to be heated from 116°C to 150°C. An upper bound of 150°C is fixed on the cold streams c1 and c3 for the reasons discussed above. The matching rules proposed for the dual temperature approach design method, can be employed for finding all possible matching combinations, whilst accounting for the constraints (Figure 6.6). Subnetworks III and IV are unconstrained and can be designed using the same matching rules (Figure 6.7 and Figure 6.8). The different possible design combinations are illustrated in Figure 6.9. The final design can be evolved by simplifying these combinations. The presence of loops can be eliminated using LONITA (Loop Network Interaction and Load Transfer Analysis). The final design in Figure 6.10 features both minimum energy consumption and minimum number of units for the given constraints. The same design was reported by Papoulias

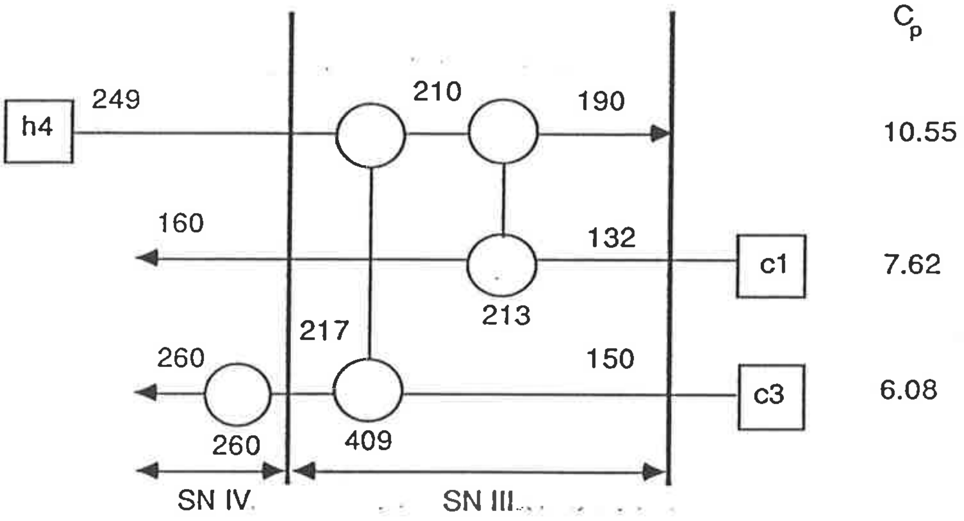


Figure 6.7: Unconstrained subnetworks III and IV (design 1)

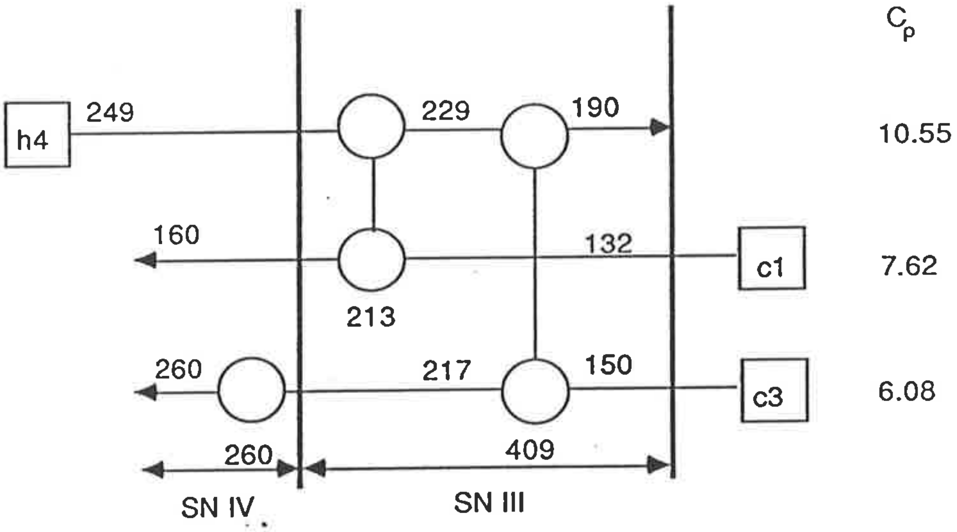


Figure 6.8: Unconstrained subnetworks III and IV (design 2)

and Grossmann [117], however, their synthesis method required the solution of a non-trivial mixed-integer linear program [MILP]. (The model in the unconstrained state involves the solution of a problem with seven binary [0-1] variables, twenty-one continuous variables and thirty constraints). Figure 6.11 illustrates an alternative final design if one assumes that 137 kW of hot utility were supplied at 160°C.

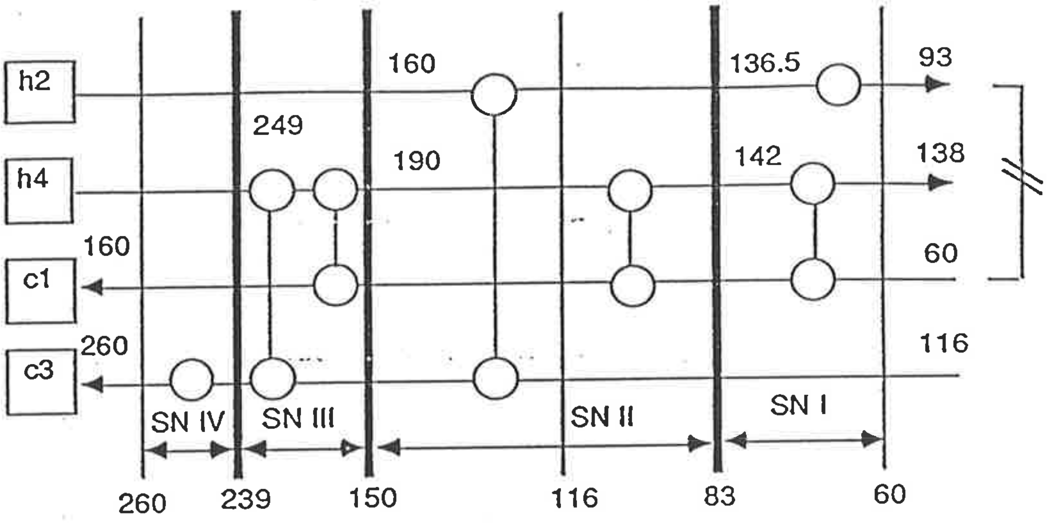
At times, the number of subnetworks can be reduced by making some simple observations. In the above example, subnetworks I and II, and subnetworks III and IV can be designed as single subnetworks. This is because both the hot streams in subnetwork I are to be cooled to their respective target temperatures. The same is true for subnetwork IV in which stream c4 has to be heated to its target temperature. (This type of problem reduction is only obvious in simple cases).

The following examples will further illustrate the simplicity and flexibility of the proposed design algorithm.

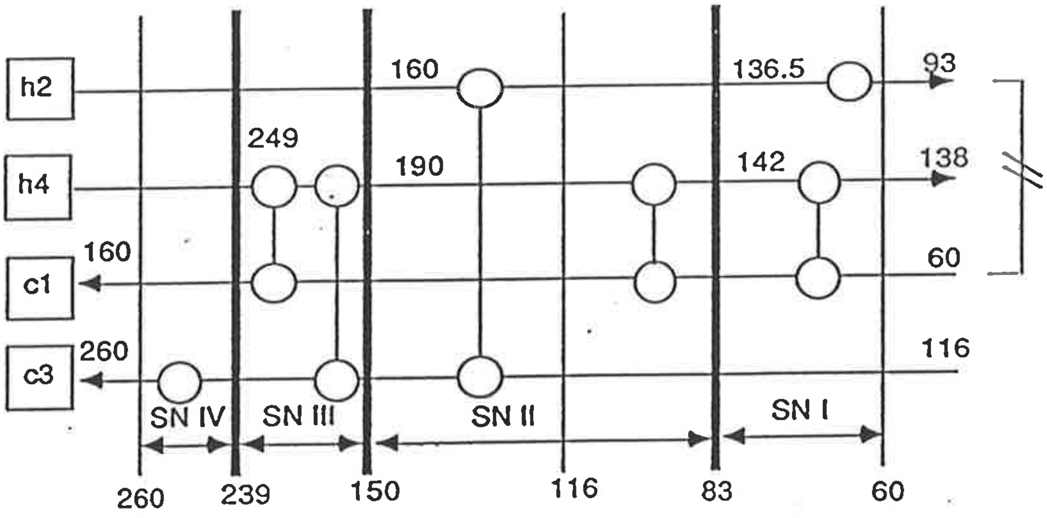
6.5 Examples

6.5.1 Example 6.2

The data for this problem is presented in Table 6.7 [20]. A match between streams c1 and h2 is prohibited above the bubble point (180°C) of stream c1. The constraint division of the problem is located at 200°C/180°C, as beyond this temperature the constraint applies. The unconstrained problem requires 116.5 kW of heating utility and 168 kW of cooling utility. The pinch point is located at 200°C/180°C. (Coincidentally, this is also the imposed constraint division point). Solution of the trans-shipment model predicts a hot utility consumption of 170 kW. The stream h2 has a residual heat of 53.5 kW at the constraint division point thus modifying its temperature at this point to be equal to 216.7°C. In general, a number of possibilities may exist for allocation of such residuals. In some instances, it may be possible to generate different topologies by varying the individual stream temperatures so that one of the stream 'slips' from one section to the next section (see previous chapter).



Design 1



Design 2

Figure 6.9: Two designs for problem 4sp1

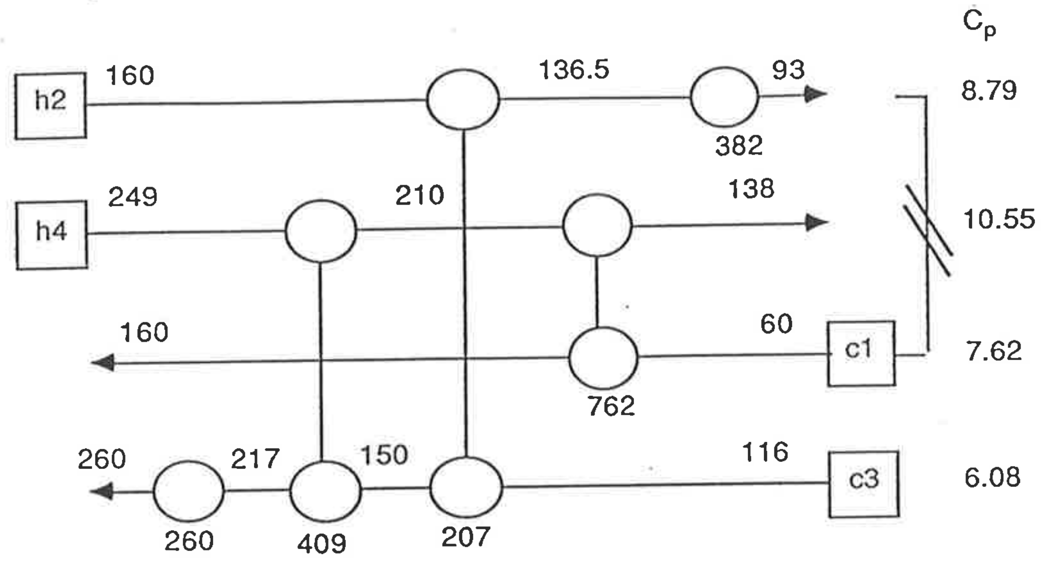


Figure 6.10: Final design with matches (c1,h2) forbidden for problem 4sp1

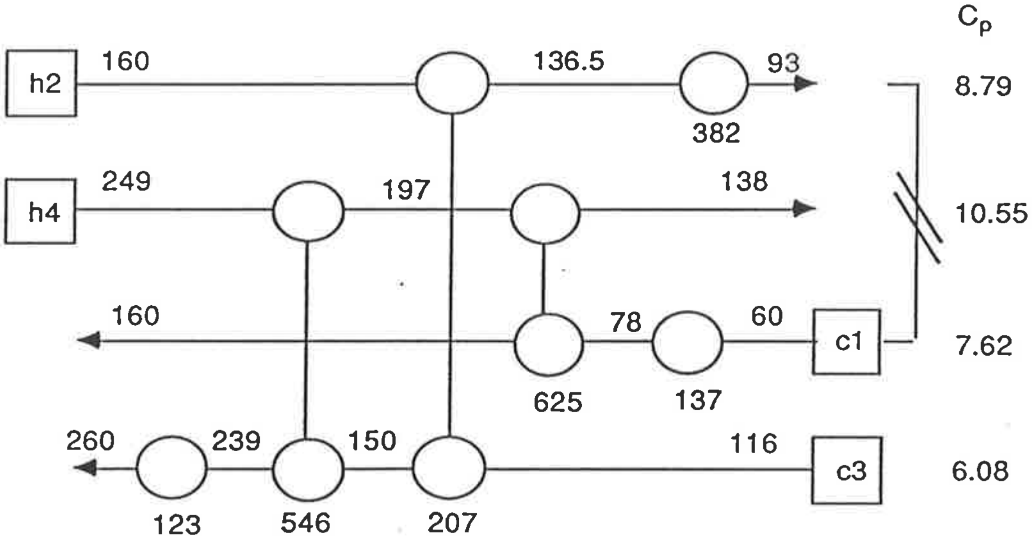


Figure 6.11: Final design with matches (c1,h2) forbidden for problem 4sp1 and 137 kW of hot utility supplied at 160°C

Table 6.7: Stream data for example 6.2 [20]

$\triangle t_{Emin} = 20$ K

Stream Number	C_p (kW/K)	Temperature Interval °C
c1	2.0	100 - 140
	2.2	140 - 180
	10.0	180 - 190
	8.0	190 - 200
	1.0	200 - 250
c2	3.9	140 - 180
	4.5	180 - 225
h1	0.6	300 - 200
	100	200 - 199
	1.2	199 - 140
h2	3.2	280 - 100

The constrained and unconstrained sub-networks for this problem along with the final designs are illustrated in Figure 6.12 - Figure 6.17. Two different topologies have been evolved, both possessing identical energy consumption.

6.5.2 Example 6.3

This example illustrates that **multiple** topologies featuring the characteristics of minimum number of units and minimum energy consumption may exist. It also illustrates the method for problems involving multiple constraints.

The data for the problem is summarized in Table 6.8. Matches (c2-h5) and(c6-h7)

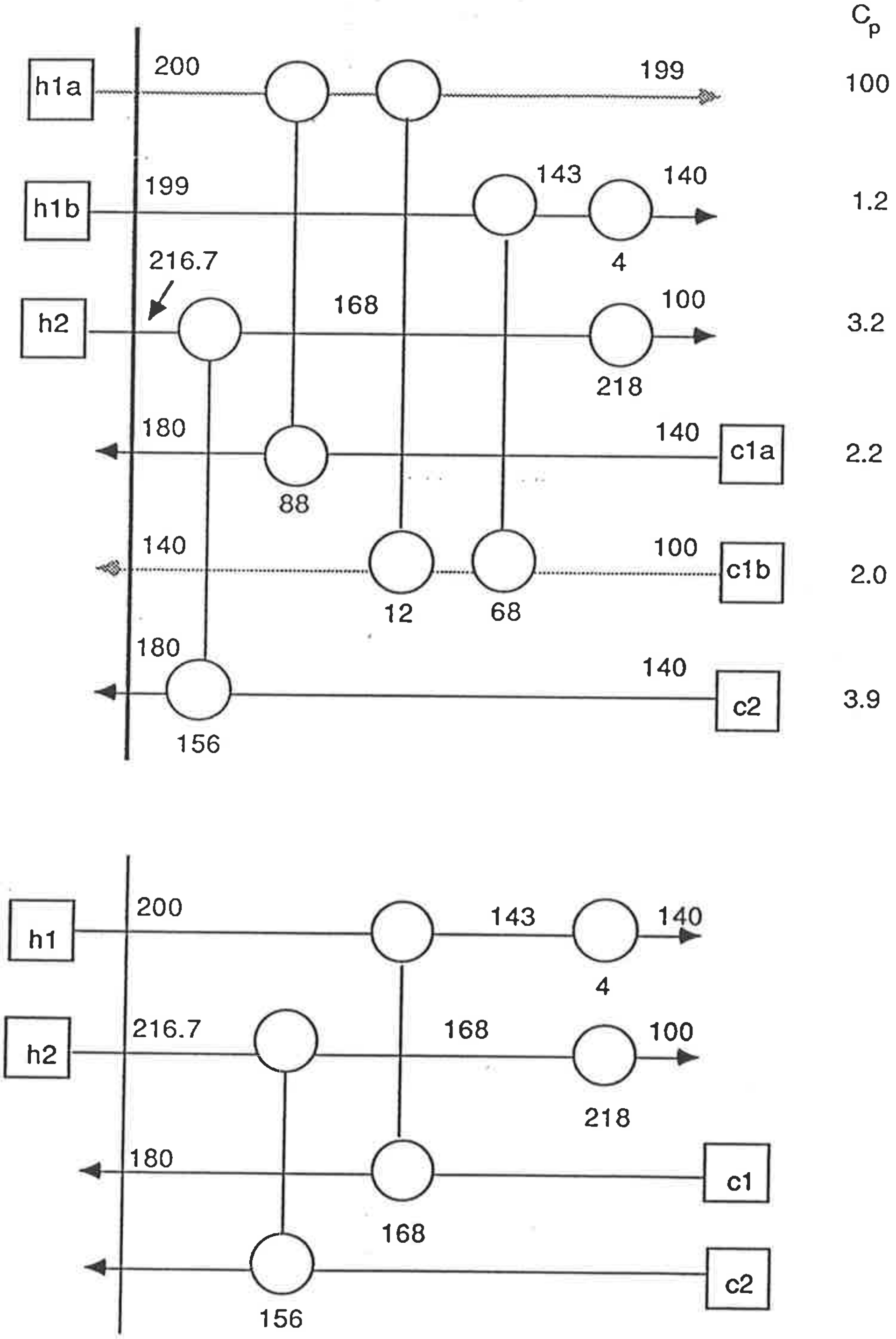


Figure 6.12: Unconstrained subnetwork 1 for example 6.2

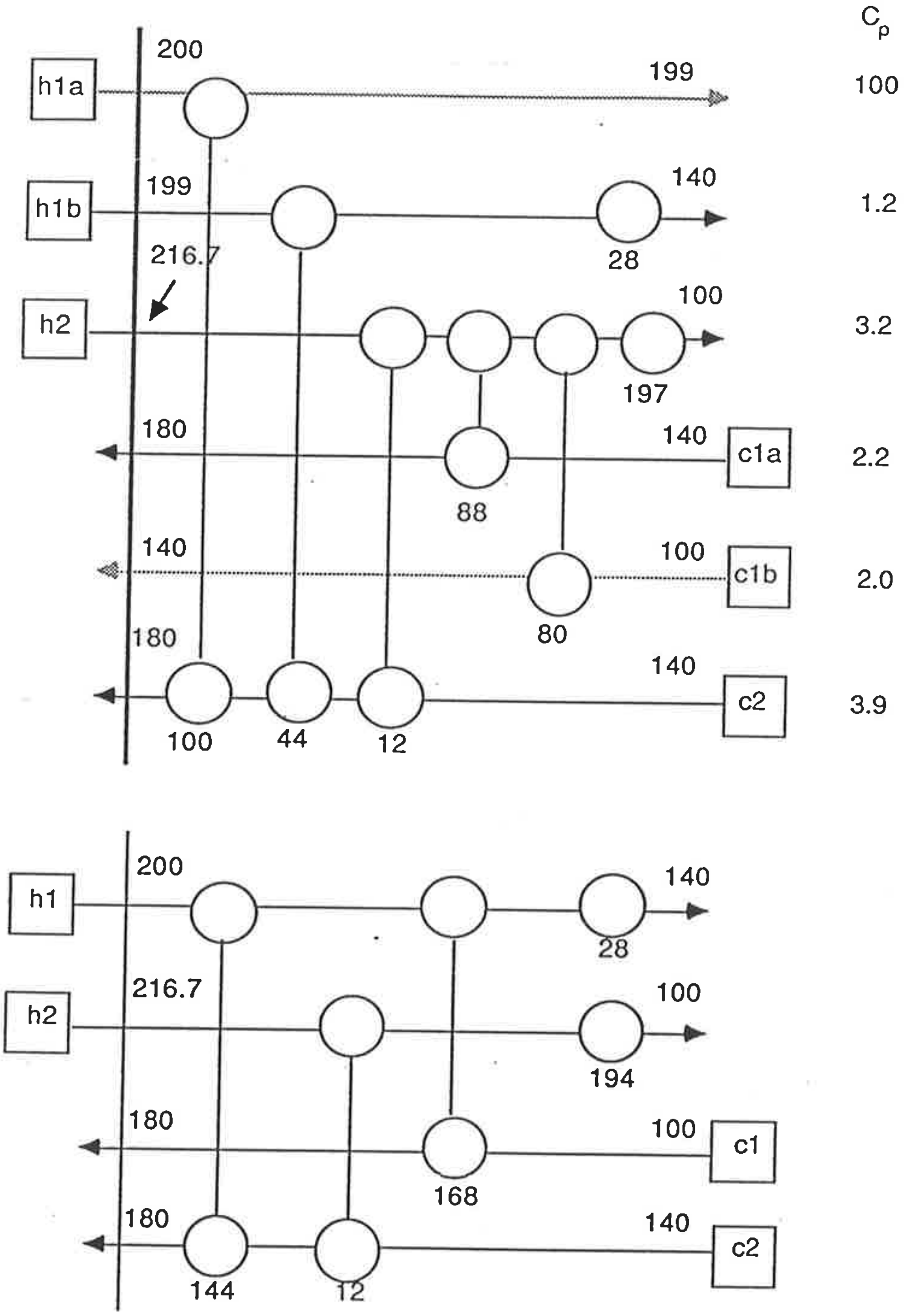


Figure 6.13: Unconstrained subnetwork 2 for example 6.2

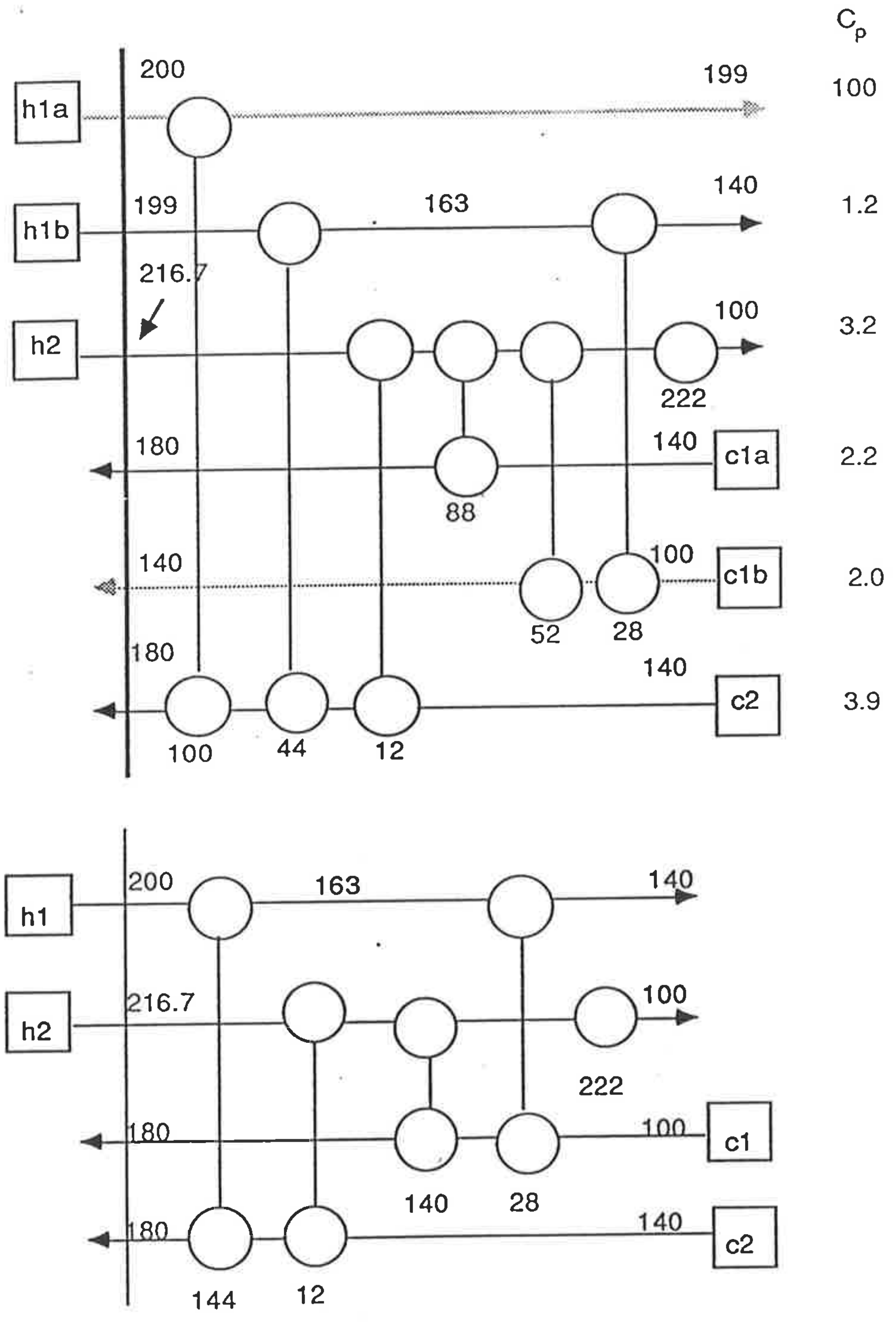
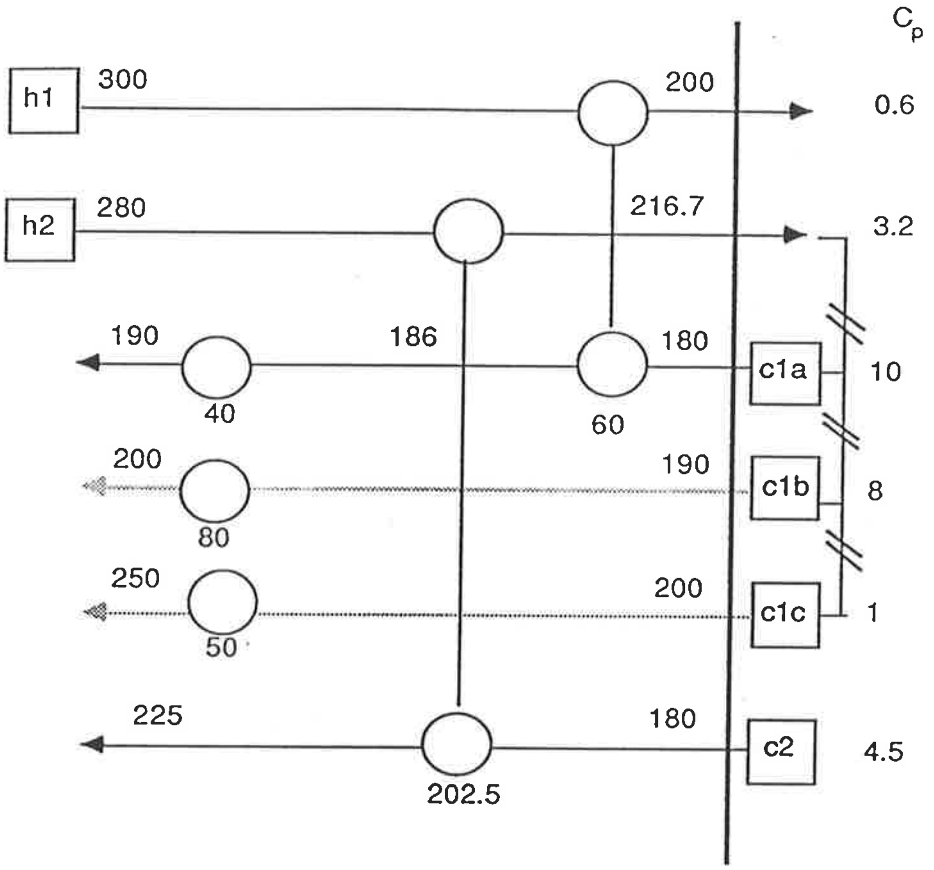


Figure 6.14: Unconstrained subnetwork 3 for example 6.2



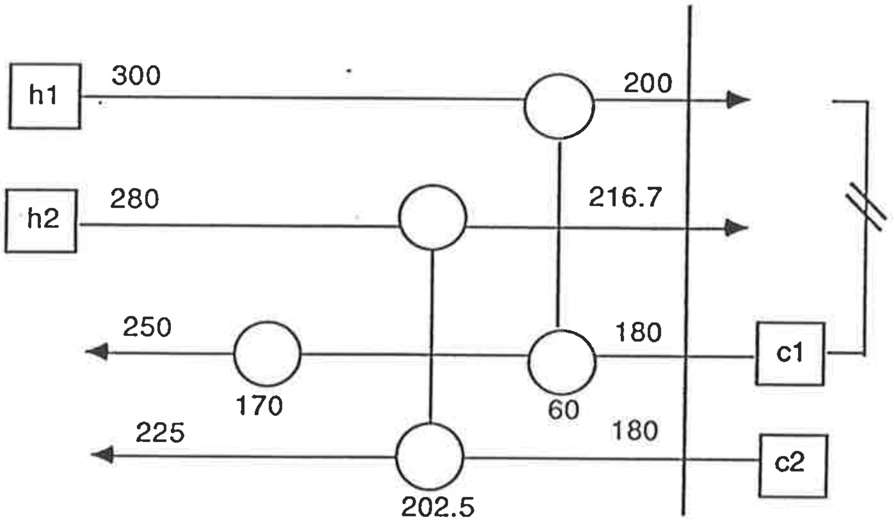


Figure 6.15: Constrained subnetwork for example 6.2

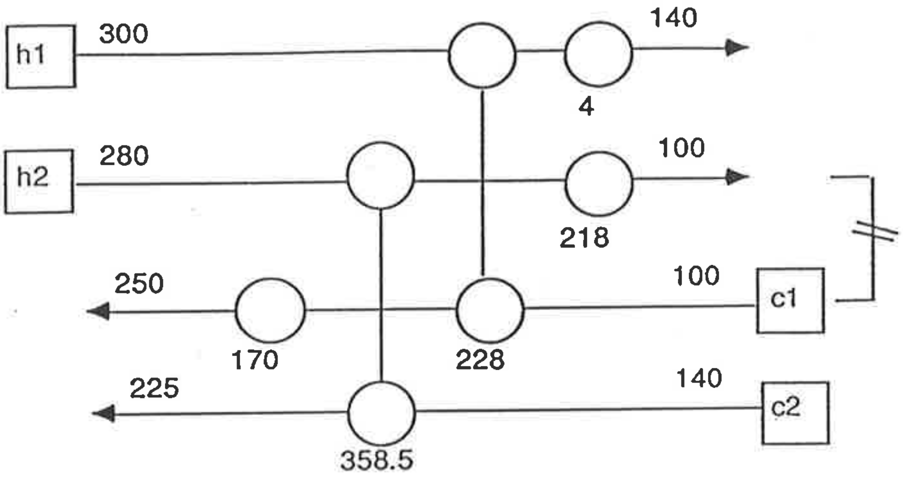


Figure 6.16: Constrained network 1 for example 6.2 featuring minimum number of units and maximum energy recovery

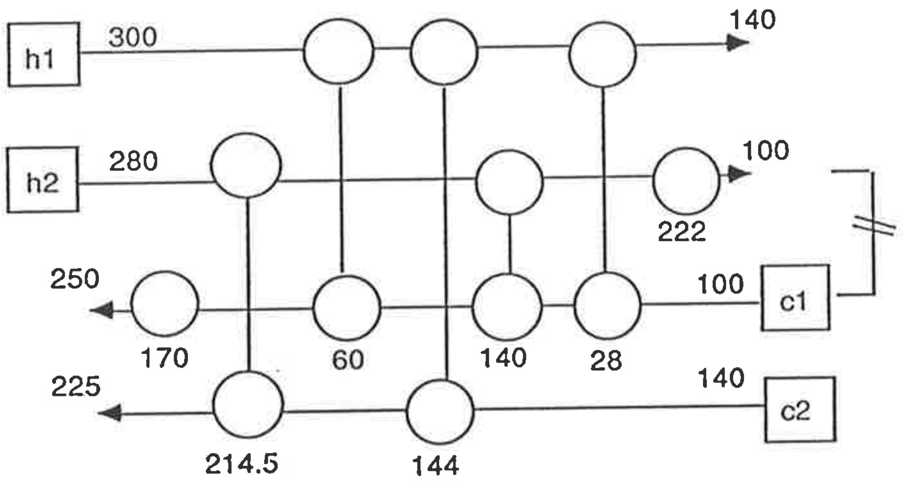


Figure 6.17: Constrained network 2 for example 6.2 featuring maximum energy recovery

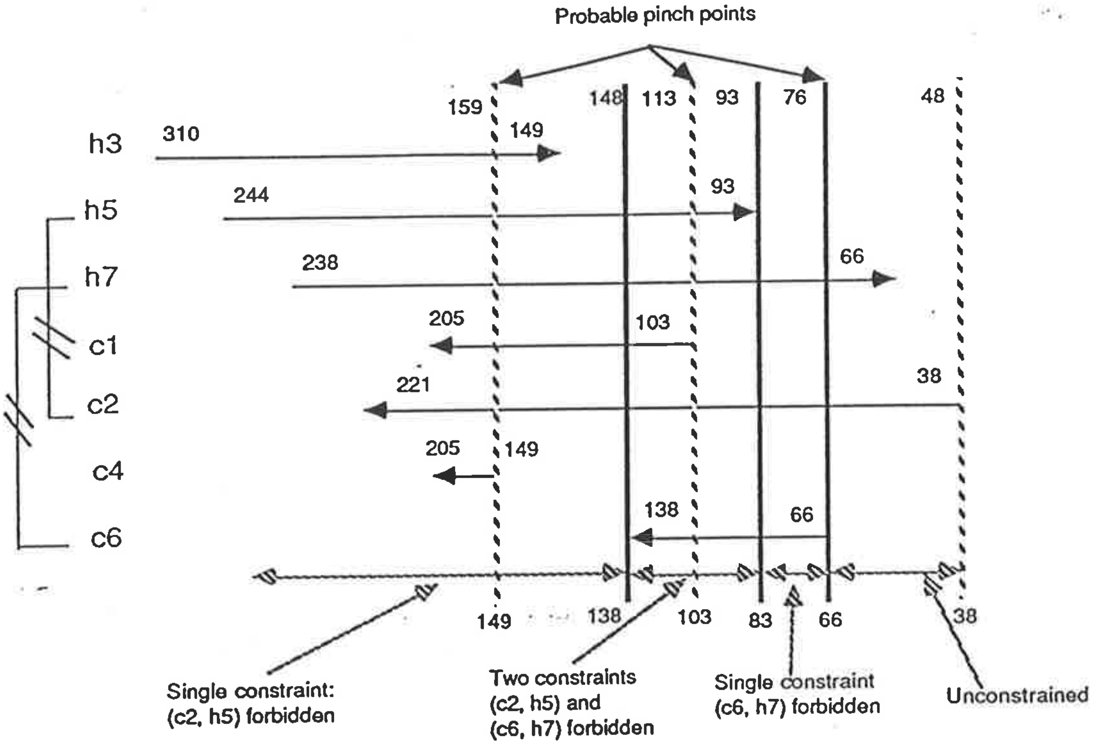


Figure 6.18: Temperature divisions to solve the trans-shipment model for example 6.3 with matches (c2,h5) and (c6,h7) forbidden

Table 6.8: Data for example 6.3 [22]

$\Delta t_{Emin} = 10$ K

Stream Number	C_p(kW/K)	T_s(°C)	T_t(°C)
c1	8.45	93	205
c2	8.44	38	221
h3	12.53	310	149
c4	19.65	149	205
h5	8.32	244	93
c6	15.50	66	138
h7	6.96	238	66

are forbidden. The sub-network divisions are presented in Figure 6.18. Prohibition of the above matches does not increase the utility consumption beyond that required for the unconstrained case. Multiple solutions are easily generated by successive reformulation of the trans-shipment linear program resulting in a theoretically-infinite number of solutions. However, in practice a large but finite set of different topologies exists. This aspect has not been reported before by any of the authors employing mathematical programming techniques [117,130], as the computer package LINDO [134] which is normally employed, fails to generate all possible solutions. Figure 6.19 - 6.21 illustrates a small variety of different topologies satisfying the imposed constraints. The previously proposed algorithm [22] failed to identify the latter two possibilities Figure 6.20 and Figure 6.21.

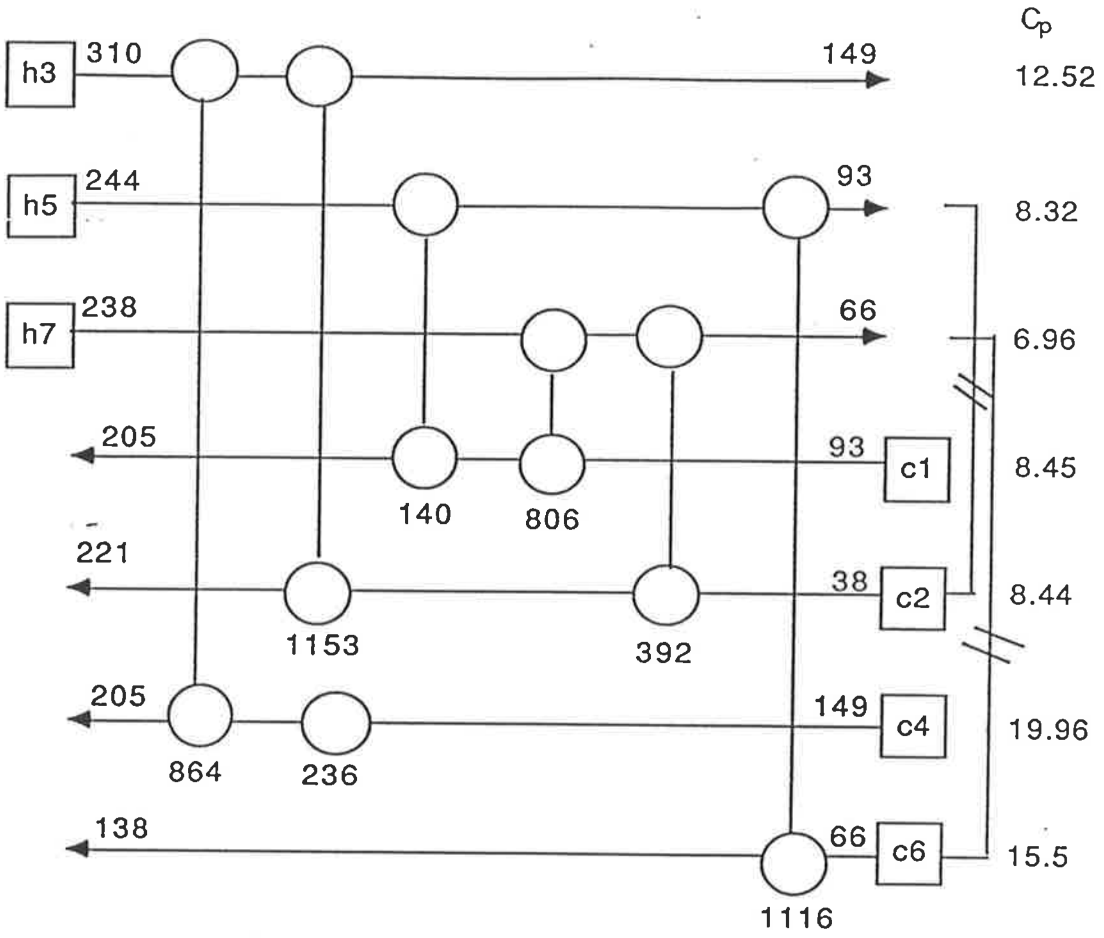


Figure 6.19: MNU, MER design 1 for example 6.3 with matches (c2,h5) and (c6,h7) forbidden [22]

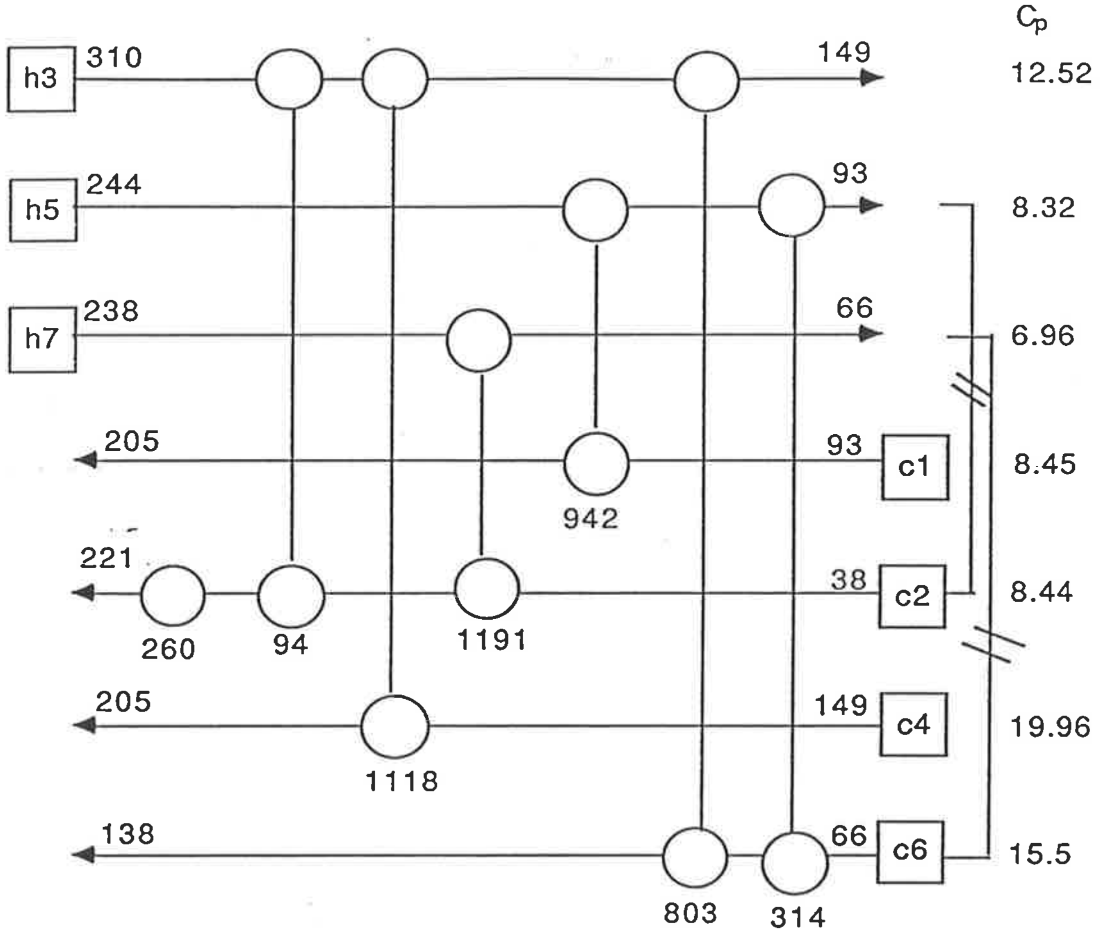


Figure 6.20: MNU, MER design 2 for example 6.3 with matches (c2,h5) and (c6,h7) forbidden

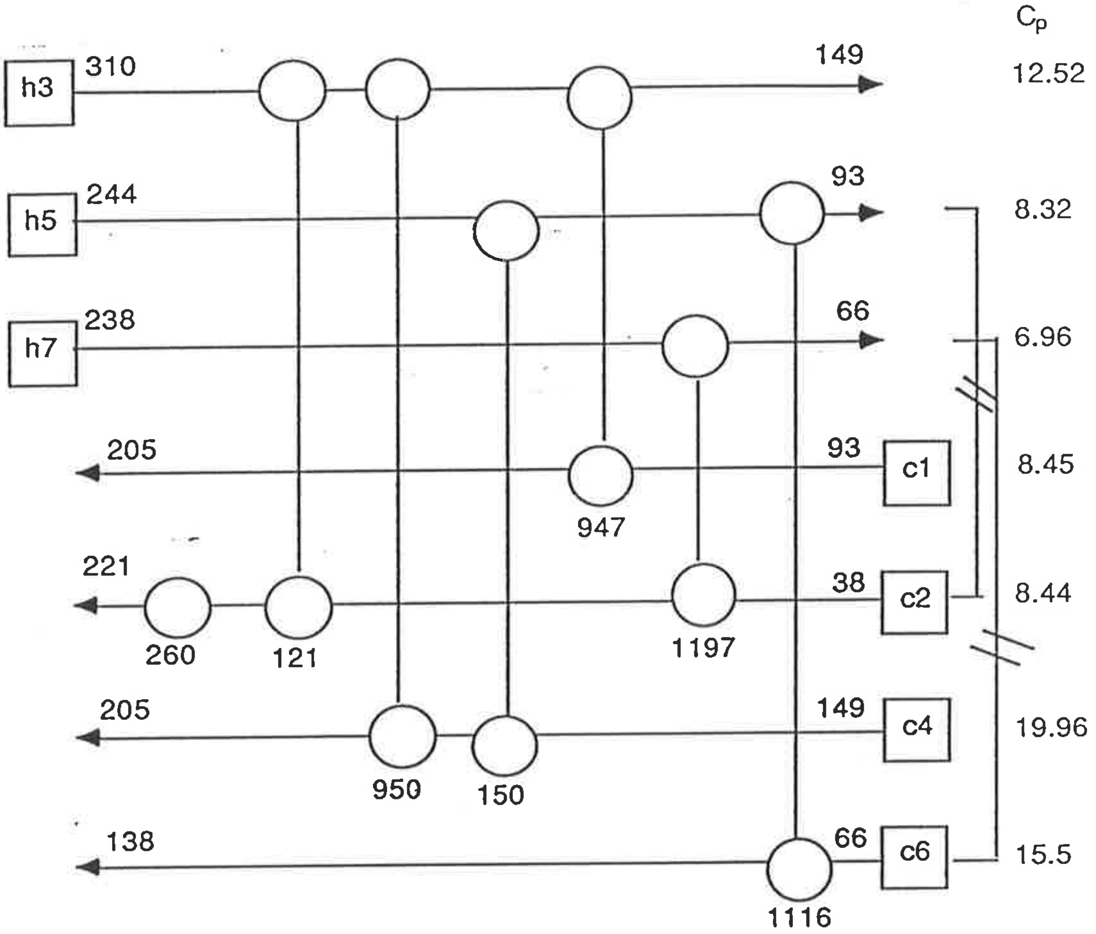


Figure 6.21: MNU, MER design 3 for example 6.3 with matches (c2,h5) and (c6,h7) forbidden

6.6 Conclusions

A simple yet flexible design method for the synthesis of heat exchanger networks incorporating user-defined constraints has been proposed. The logic of the synthesis procedure is summarized as Figure 6.22. The outlined strategy, namely, dividing the problem at the temperatures where the number of imposed constraints changes and then sequentially designing the network from the cold end, is an entirely new approach. The dual approach temperature method which incorporates explicit rules for identifying all possible matching combinations and indicates when stream should be split, may be employed to generate a set of feasible network topologies. The ease of application and the realization of the fact that multiple solutions exist for a given energy consumption, allows the designer to quickly explore alternative practical topologies and evolve the final "best" solution with minimal effort.

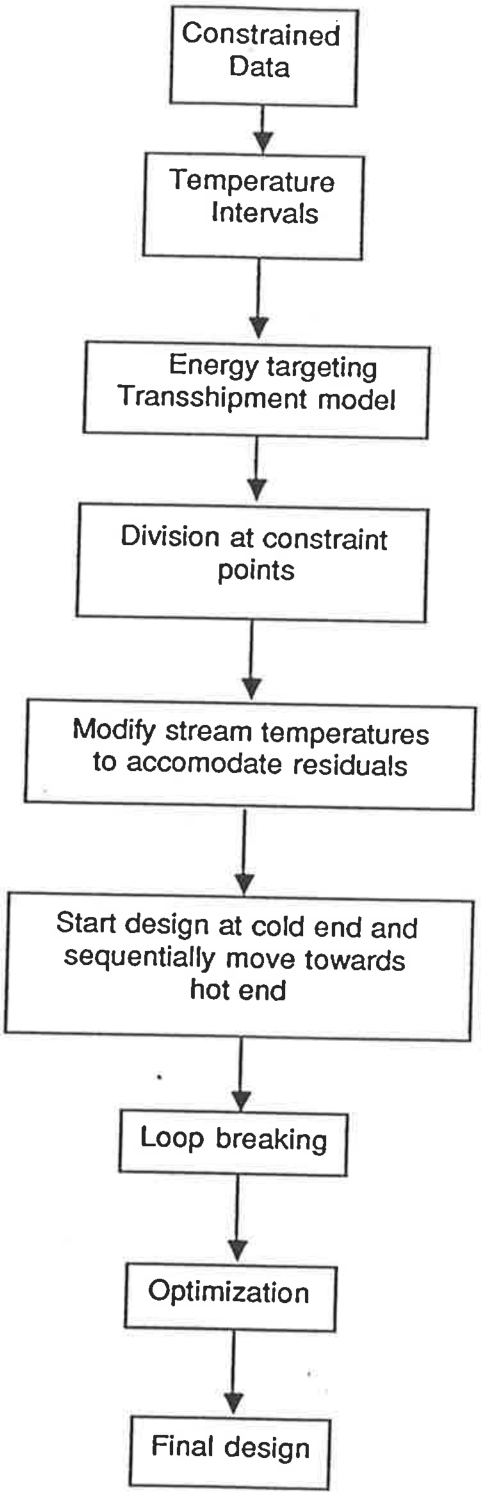


Figure 6.22: Summary of the proposed design procedure

Chapter 7

Conclusions and Recommendations for Future Work

7.1 Introduction

In this chapter some of the problems which did not fit into the general discussion of the previous chapters are considered. Some problems are discussed in detail and for others plausible schemes for further investigation are presented. Extensions of the pinch design method and the dual temperature design method (setting targets of some important design parameters, extension to total plant integration and retrofit situations) are discussed. Finally, ideas for a proposed new design procedure for the constrained match case is introduced including extensions to total process plant integration.

7.2 Handling Match Dependent $\triangle t$

Cerda et al. [20] introduced the concept of match dependent $\triangle t$. For energy targeting, they have modified the projection rules proposed for targeting the energy consumption for a global value of $\triangle t_{min}$ (see chapter 2). Townsend and Linnhoff [152] have suggested the use of a $\triangle t$ "contribution" method and have successfully applied the concept for targeting and design of heat exchanger networks. However, other targets such as area, shell and the optimum value of $\triangle t$ are yet to be established for this case.

In this thesis, the importance of composite curves for obtaining an area target, a shell target, and locating the region in which the optimum value of $\triangle t_{min}$ is likely to be found has been reported. It could be rewarding to develop composite curves to handle the match dependent $\triangle t_{min}$ case as it represents a more practical situation. The assumption of global $\triangle t_{min}$ is overly restrictive. In practical situations match-dependent $\triangle t_{min}$ may be required due to the following:

- refrigeration
- flowrate variations
- corrosive materials
- to incorporate vapour-vapour matches and/or vapour-liquid matches

7.2.1 Proposed Composite Curves for Match Dependent $\triangle t$'s

The generation of the composite curves is based on the concept of $\triangle t_{min}$ "contribution" [152]. Here a new method is proposed which introduces the idea of **effective contribution**. It can best be illustrated by an example. Table 7.1 details the stream data along with their individual stream contribution.

Stream 1 and 4 have a $\triangle t_{min}$ of 10 K (5+5) which is the minimum for all possible

Table 7.1: Data for example 7.1

Stream Number	C_p(kW/K)	T_s(°C)	T_t(°C)	Δt_{con}
1	2	20	135	5
2	3	170	60	10
3	4	80	140	20
4	1.5	150	30	5

matches. Hence, this problem has a global minimum match dependent Δt^M_{min} of 10K. The **effective contribution** of stream 2 towards a match Δt will be 5 K and that of stream 3 will be 15 K. The starting and target temperatures of these streams can be reduced/increased by their respective effective contributions. The "modified" data is tabulated in Table 7.2.

The *effective* Δt contribution of streams 1 and 4 is 0 K. The starting and target temperatures of the hot stream are reduced by their respective effective Δt contribution and that of the cold stream are increased. The data modified in the above table has a global minimum approach temperature of 10 K. The composite curves can be generated in the usual way and are illustrated in Figure 7.1 for the example under consideration. It should be noted that the energy targets from the composite curves are the same as those obtained by using the modified problem table analysis of Townsend and Linnhoff [152]. Henceforth, these curves shall be referred to as *match dependent composite curves.*

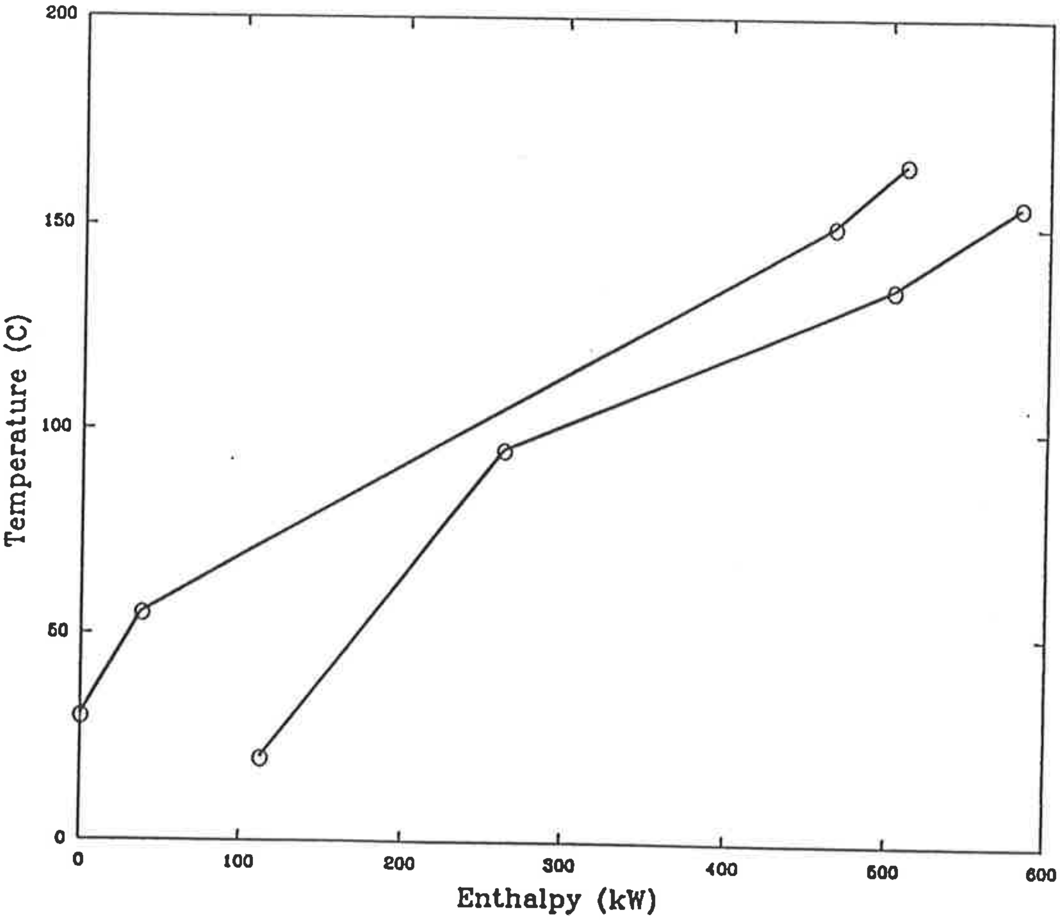


Figure 7.1: Composite curves for data of example 7.1

Table 7.2: Modified data for example 7.1

$\triangle t^{M}_{min} = 10$ K

Stream Number	C_p(kW/K)	T'_s(°C)	T'_t(°C)
1	2	20	135
2	3	165	55
3	4	95	155
4	1.5	150	30

7.2.2 A Proposed Area Target for Match Dependent $\triangle t_{min}$'s

A method similar to that of Townsend and Linnhoff [151] can be developed for obtaining an area target to handle the match dependent $\triangle t_{min}$ situation. The match dependent composite curves can be divided at the kink points into different sections (see chapter 2). A "spaghetti" network as illustrated in Figure 7.2 can be designed for each section [101]. This design is obtained by splitting each cold stream such that the number of stream splits on any stream is equal to the total number of hot streams in that section. Hot streams are similarly split. A simple network in which all the cold streams are matched with all the hot streams can be generated and is illustrated in Figure 7.2. The *effective* contribution of hot and cold streams is denoted by $\triangle t^{hi}_{ec}$ and $\triangle t^{cj}_{ec}$ respectively.

The C_p values of the individual stream splits is dependent on the match in the spaghetti design. Thus, the C_p of split stream 3 which exchanges heat in exchanger 1 (Figure 7.2) is given by

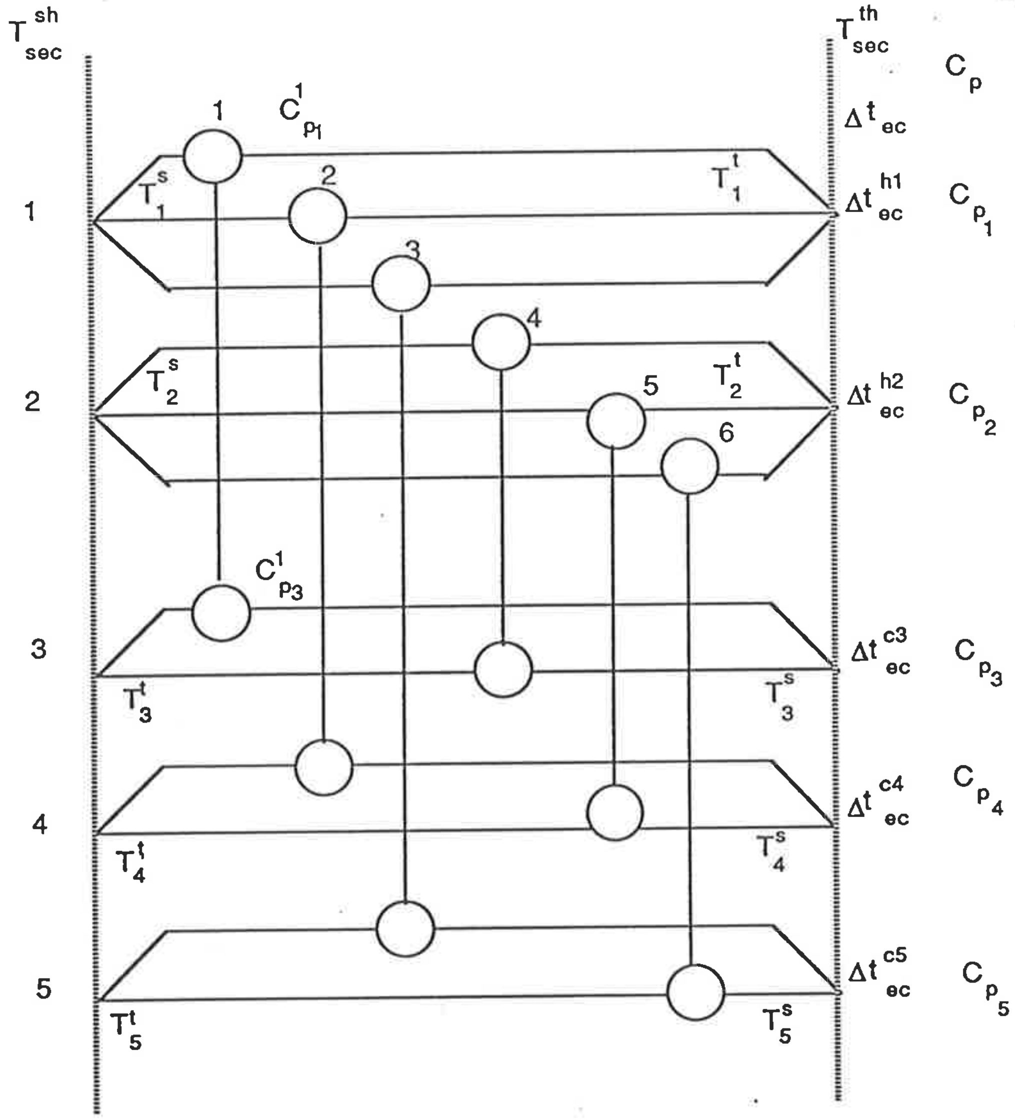


Figure 7.2: “Spaghetti” design

$$C^1_{p3} = \frac{C_{p_3}}{C_{p_1} + C_{p_2}} \times C_{p_1} \tag{7.1}$$

Alternatively, the C_p of the split hot stream 1 is given by

$$C^1_{p1} = \frac{C_{p_1}}{C_{p_3} + C_{p_4} + C_{p_5}} \times C_{p_3} \tag{7.2}$$

In general, the C_p of the split cold stream j which exchanges heat with the split hot stream i in exchanger e is given by,

$$C'^{e}_{pj} = \frac{C_{pj} \times C_{pi}}{\sum_i^{N_{hot}} C_{pi}} \tag{7.3}$$

Similarly,

$$C'^{e}_{pi} = \frac{C_{pi} \times C_{pj}}{\sum_j^{N_{cold}} C_{pj}} \tag{7.4}$$

The area of this section k is given by

$$A_k = A_1 + A_2 + A_3 + A_4 + A_5 + A_6 \tag{7.5}$$

Consider exchanger unit 1. The area of this unit A_1 is,

$$A_1 = \frac{Q_1}{U_1 \triangle T_{LM_1}} \tag{7.6}$$

$$A_1 = \frac{Q_1}{\Delta T_{LM_1}} \times \left(\frac{1}{h_1} + \frac{1}{h_3}\right) \tag{7.7}$$

It can be conservatively assumed that $\Delta T_{LM} = \Delta T_{av}$. Thus,

$$A_1 = \frac{Q_1}{\Delta T_{av_1}} \times \left(\frac{1}{h_1} + \frac{1}{h_3}\right) \tag{7.8}$$

$$\triangle T_{av} = \frac{(T_1^s - T_3^t) + (T_1^t - T_3^s)}{2} \tag{7.9}$$

But,

$$T_1^s = T_{sec}^{sh} + \Delta t_{ec}^{h1}$$

$$T_1^t = T_{sec}^{th} + \Delta t_{ec}^{h1}$$

$$T_3^t = T_{sec}^{tc} - \Delta t_{ec}^{c3}$$

$$T_3^s = T_{sec}^{sc} - \Delta t_{ec}^{c3}$$

Substituting these into the previous equations we get

$$\triangle T_{av} = \frac{(T_{sec}^{sh} - T_{sec}^{tc}) + (T_{sec}^{th} - T_{sec}^{sc}) + 2(\Delta t_{ec}^{h1} + \Delta t_{ec}^{c3})}{2} \tag{7.10}$$

$$\triangle T_{av} = \frac{\Delta T_{sec}}{2} + \Delta t_{ec}^{h1} + \Delta t_{ec}^{c3} \tag{7.11}$$

$$\triangle T_{av} = \Delta T_{sec}^{av} + \Delta t_{ec}^{h1} + \Delta t_{ec}^{c3} \tag{7.12}$$

Therefore,

$$A_1 = \frac{Q_1}{\Delta T_{sec}^{av} + \Delta t_{ec}^{h1} + \Delta t_{ec}^{c3}} \left(\frac{1}{h_1} + \frac{1}{h_3}\right) \tag{7.13}$$

But,

$$Q_1 = \frac{C_{p_1} \times C_{p_3}(T_3^t - T_3^s)}{(C_{p_1} + C_{p_2})} \tag{7.14}$$

Hence,

$$A_1 = \frac{C_{p_1} \times C_{p_3}(T_3^t - T_3^s)}{(C_{p_1} + C_{p_2})(\Delta T_{sec}^{av} + \Delta t_{ec}^{h1} + \Delta t_{ec}^{c3})} \left(\frac{1}{h_1} + \frac{1}{h_3}\right) \tag{7.15}$$

Substituting $\Delta H_3 = C_{p_3}(T_3^t - T_3^s)$ which is the heat load of stream 3 in this section in the above equation,

$$A_1 = \frac{C_{p_1} \times \Delta H_3}{(C_{p_1} + C_{p_2})(\Delta T_{sec}^{av} + \Delta t_{ec}^{h1} + \Delta t_{ec}^{c3})} \left(\frac{1}{h_1} + \frac{1}{h_3}\right) \tag{7.16}$$

Similarly,

$$A_2 = \frac{C_{p_1} \times \Delta H_4}{(C_{p_1} + C_{p_2})(\Delta T^{av}_{sec} + \Delta t^{h1}_{ec} + \Delta t^{c4}_{ec})} \left(\frac{1}{h_1} + \frac{1}{h_4} \right) \tag{7.17}$$

$$A_3 = \frac{C_{p_1} \times \Delta H_5}{(C_{p_1} + C_{p_2})(\Delta T^{av}_{sec} + \Delta t^{h1}_{ec} + \Delta t^{c5}_{ec})} \left(\frac{1}{h_1} + \frac{1}{h_5} \right) \tag{7.18}$$

$$A_4 = \frac{C_{p_2} \times \Delta H_3}{(C_{p_1} + C_{p_2})(\Delta T^{av}_{sec} + \Delta t^{h2}_{ec} + \Delta t^{c3}_{ec})} \left(\frac{1}{h_2} + \frac{1}{h_3} \right) \tag{7.19}$$

$$A_5 = \frac{C_{p_2} \times \Delta H_4}{(C_{p_1} + C_{p_2})(\Delta T^{av}_{sec} + \Delta t^{h2}_{ec} + \Delta t^{c4}_{ec})} \left(\frac{1}{h_2} + \frac{1}{h_4} \right) \tag{7.20}$$

$$A_6 = \frac{C_{p_2} \times \Delta H_5}{(C_{p_1} + C_{p_2})(\Delta T^{av}_{sec} + \Delta t^{h2}_{ec} + \Delta t^{c5}_{ec})} \left(\frac{1}{h_2} + \frac{1}{h_5} \right) \tag{7.21}$$

The total area of the section k is

$$A_k = \frac{1}{\sum_i C_{p_i}} \left[\sum_i \sum_j \frac{C_{p_i} \times \Delta H_j}{\Delta T^{av}_{sec} + \Delta t^{hi}_{ec} + \Delta t^{cj}_{ec}} \left(\frac{1}{h_i} + \frac{1}{h_j} \right) \right] \tag{7.22}$$

But, the minimum area of the network A_{min} is

$$A_{min} = \sum_k A_k \tag{7.23}$$

$$A_{min} = \sum_k \left(\frac{1}{\sum_i C_{p_i}} \left[\sum_i \sum_j \frac{C_{p_i} \times \Delta H_j}{\Delta T^{av}_{sec} + \Delta t^{hi}_{ec} + \Delta t^{cj}_{ec}} \left(\frac{1}{h_i} + \frac{1}{h_j} \right) \right] \right)_k \tag{7.24}$$

It is speculated that shell targets can be predicted using a modification of the procedure outlined in chapter 3. Assuming an exponential cost equation, the optimum value of Δt^{M}_{min} can also be predicted by a procedure similar to the one outlined in the same chapter.

7.3 Pinch Point and Threshold Problems

Linnhoff and Hindmarsh [91] have classified the problem data into two types. Designs of the first type (problems in which a pinch exists) have been discussed by them in detail. The second type are known as *threshold problems.* This type of problem only needs one utility i.e. either hot or cold, but not both. The problem does not have a pinch point. In arriving at this classification they defined the pinch point as the temperature at which there is zero heat flow in the heat cascade of the problem table analysis.

Another definition of the pinch point was given by Saboo and Morari [133]. They employed the cumulative deficit method of Raghavan [126]. Cumulative deficit is defined as follows:

$$h(T) = \int_{T}^{T_M} C_p(T')dT' \tag{7.25}$$

$$H = max_T \; h(T) = max_T \int_{T}^{T_M} C_p(T')dT' \tag{7.26}$$

The pinch point according to this method is defined as the temperature at which $h(T)$ reaches its global maximum H. According to this definition there will always be a pinch point.

If the pinch point is defined as the point of closest approach temperature of the composite curves, then a pinch point will always exist (with the limiting case at one end). In such a situation, contrary to the existing theory, cold utilities will be used above the pinch point and hot utilities will be used below the pinch point. But instead of degrading heat and using extra utilities, heat can be transferred across the pinch point, thus reducing the total utility requirement. As the positions of the heat source and sink are opposite to the ones exhibited by the conventional pinch problems, these type of problems are referred as “sink-source inversion problems”. This concept and the design of such problems will now be illustrated by examples.

Table 7.3: Data for example 7.2

$\Delta t_{min} = 10$ K

Stream Number	C_p(kW/K)	T_s(°C)	T_t(°C)
1	1	310	50
2	2	450	280
3	3	40	120
4	2	115	290

The pinch design rules as well as the pseudo-pinch design rules can now be used for designing the network.

Consider the data tabulated in Table 7.3. As foreshadowed above, the problem table analysis indicates that there is no pinch point. A cold utility of 10 kW is required. According to the cumulative deficit method, the pinch point is predicted as 450-440 °C which is erroneous. The predicted cold utility consumption is the same as that found by the problem table analysis. The composite curves for the above data is illustrated in Figure 7.3. The pinch point on these curves is 50-40 °C. Hence, all the above methods predict three different pinch points. If a Δt_{min} of 5 K is assumed, then the composite curves illustrated in Figure 7.4 show that the pinch point is 50-45 °C and 15 kW of heating will be required below the pinch point and 25 kW of cooling will be required above the pinch point. As the 25 kW of cooling is required at a higher temperature it can be used for the heating required below the pinch point. Thus 15 kW of heat will have to be transferred across the pinch point and the total utility requirement will decrease to 10 kW of cooling. Employing this

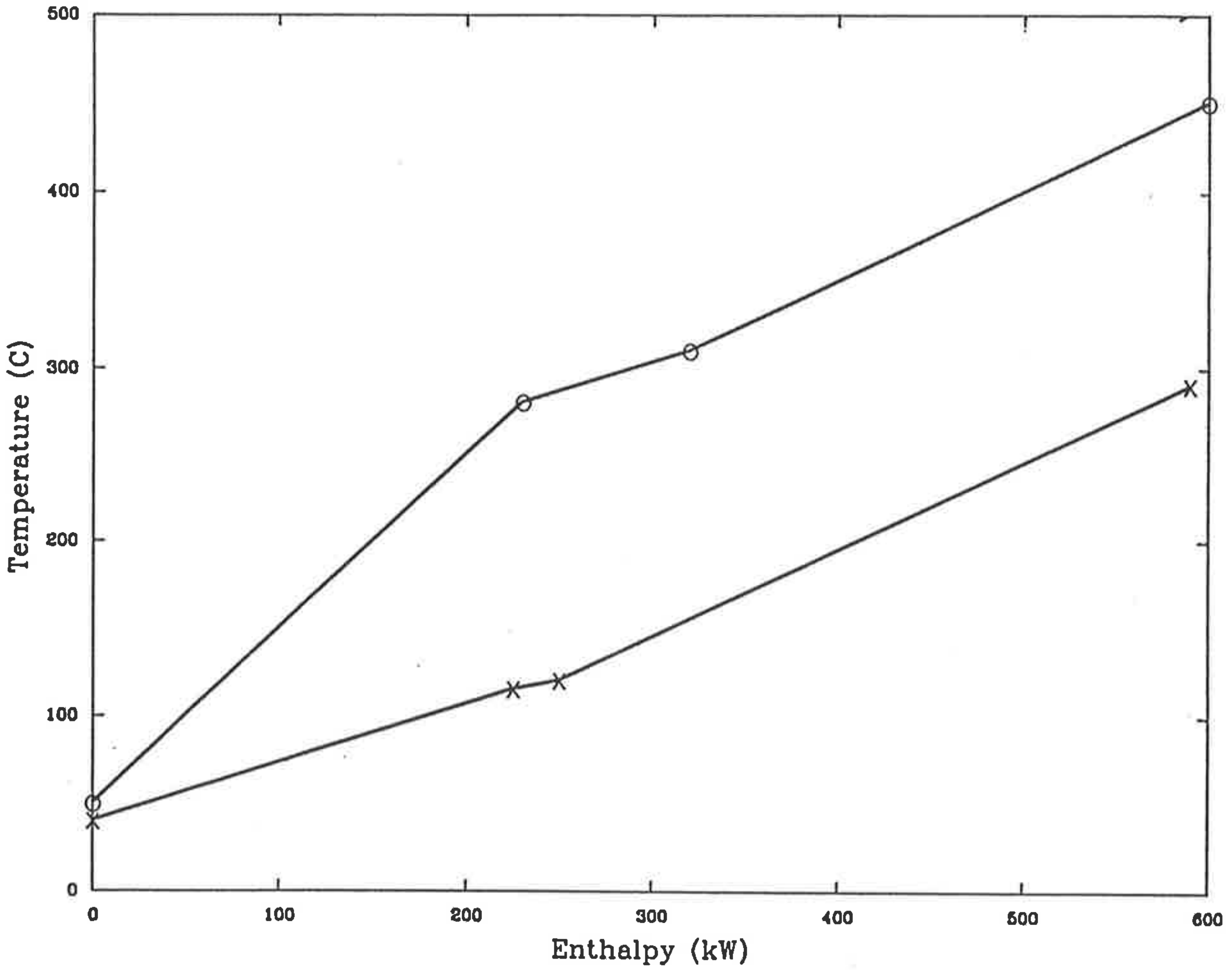


Figure 7.3: Composite curves for example 7.2 with $\Delta t_{min} = 10$ K

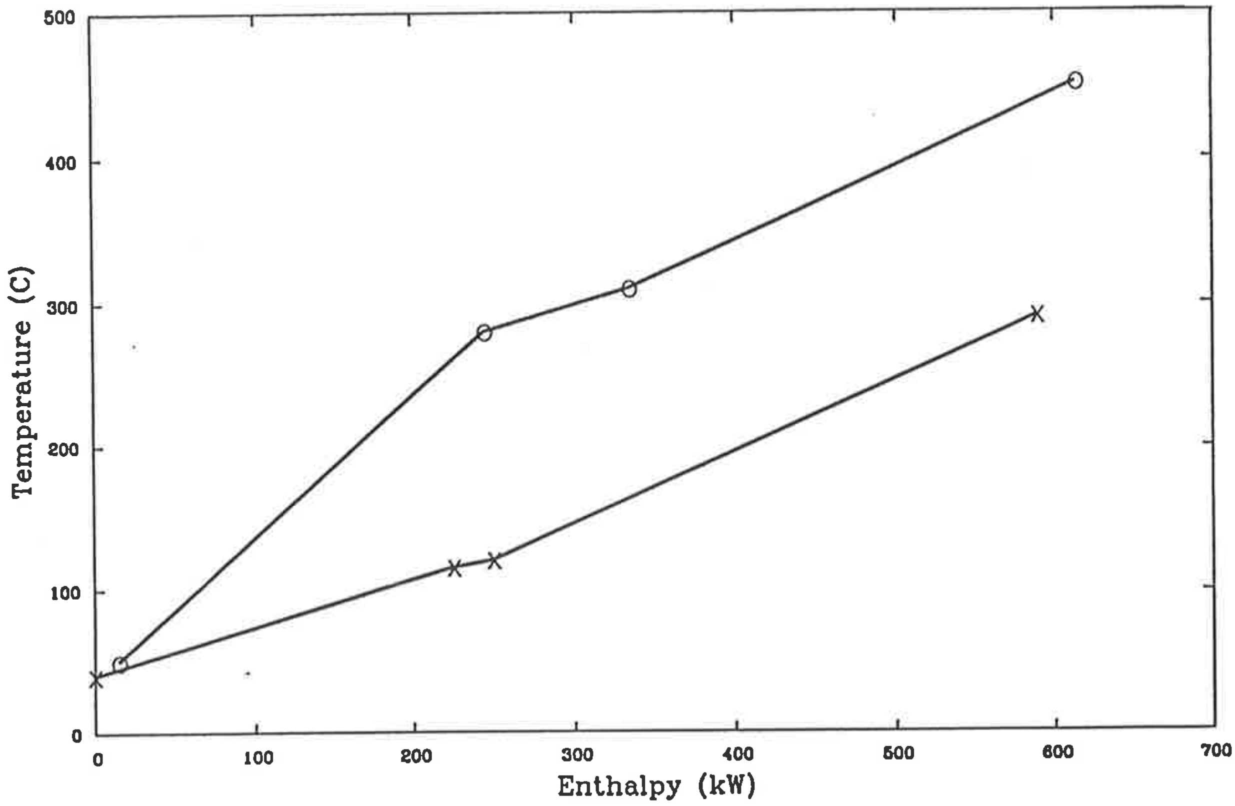


Figure 7.4: Composite curves for example 7.2 with $\Delta t_{min} = 5$ K

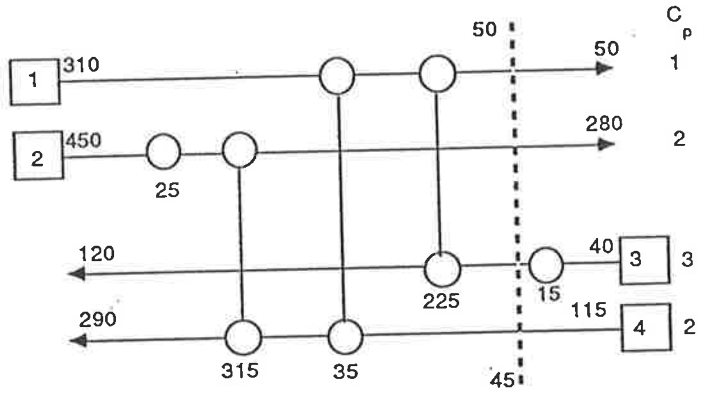


Figure 7.5: Network obtained using the pinch point as 50-45 °C

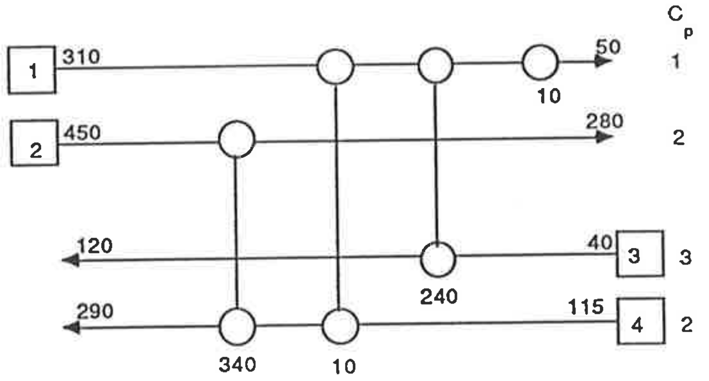


Figure 7.6: Evolved network 1

pinch point for $\Delta t_{min} =$ 5 K, a grid diagram illustrating the network obtained is shown in Figure 7.5. Two different topologies can be evolved from this initial design as illustrated in Figure 7.6 and Figure 7.7. The later one is obtained by seeding the network with a dummy cooler. It should be noted that the proposed new method is more systematic than the existing pinch design method for threshold problems.

To illustrate this concept further consider the data tabulated in Table 7.4 [47]. This is a special case of a threshold problem. The pinch point on the composite curves is located at 360 - 350 °C. The problem table shows a zero heat flow at 330 -

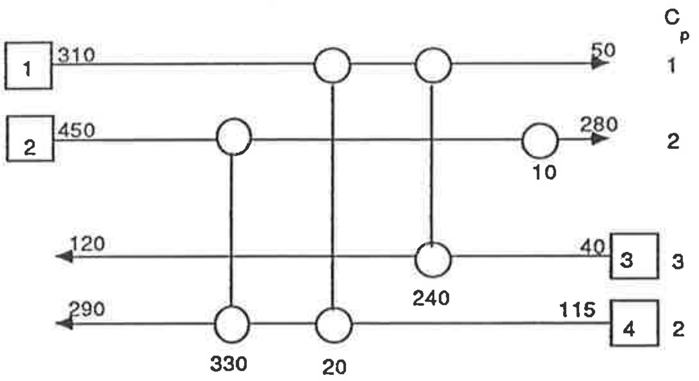


Figure 7.7: Evolved network 2

Table 7.4: Data for example 7.3 [47]

$\Delta t_{min} = 10$ K

Stream Number	C_p(kW/K)	T_s(°C)	T_t(°C)
1	1	450	350
2	1.2	450	350
3	1	320	400
4	2	350	420

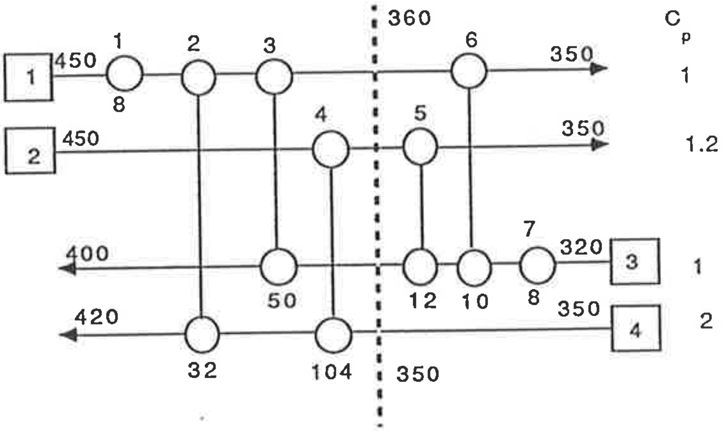


Figure 7.8: Pinch design for example 7.3

320 °C which obviously is not the pinch point. A design for this data with the pinch division is illustrated in the Figure 7.8. The final evolved design features four units as illustrated in Figure 7.9. A design with less than this number of units cannot be obtained for this problem. The existence of a pinch point gives an explanation to support this statement. The final design is generated by removing the heaters and the coolers which have the same heat load. These can be easily predicted from the start. Hence, the $U_{min_{MER}}$ target will be 5. However, units 3 and 6 form a first level loop and the streams in these matches have the same C_p value, so they can be merged without any energy penalty. The loop present in the final design is a locked loop (refer chapter 4) as units 2 and 3 are adjacent and are of type A. Assigning 8 kW of heat that is transferred across the pinch point to stream 2, the final design can be directly obtained without any evolution using the dual temperature approach design method.

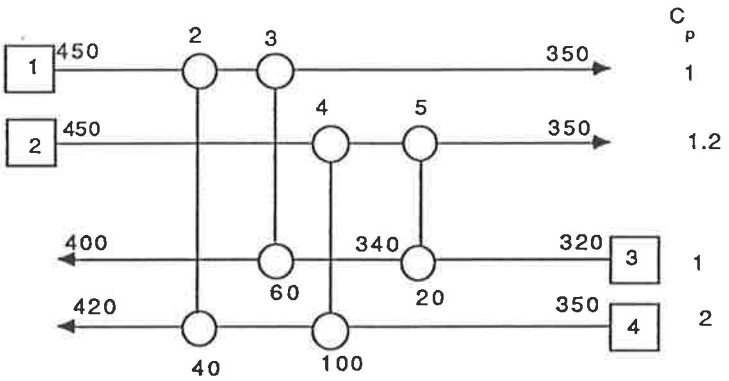


Figure 7.9: Evolved network for example 7.3

7.4 Energy Relaxation

In chapter 4 the problem of energy relaxation in an MER design was discussed. It was assumed that the designer's objective was to minimize the energy penalty when a unit was removed as a step in lowering the total effective cost. However, a better objective would be the direct minimization of the overall cost of the network. The same formulation and search technique (see chapter 4) can be employed in the modified problem with the objective of minimizing the overall network cost, provided a suitable heuristic estimator for predicting a conservative[1] estimate of the network cost can be developed. Such an estimator could be obtained from the area-energy curve [56]. For a given total energy consumption, the minimum network area can be obtained from this curve and can be used in the cost equation to predict a conservative cost estimate. The 'best-first' search can then be applied in the usual

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[1] for a 'best-first' search

way to arrive at an optimal solution. Further investigation is needed along these lines.

7.4.1 Genetic Algorithm

As the problem of unit reduction with minimum energy penalty is quiet complex and the solution to a MINLP is not a trivial task, better solution methods are required to handle this problem. Recently, Genetic Algorithms (GA)[2] have gained a lot of popularity in solving problems with similar attributes, eg. as an alternative to MINLP for solving the travelling salesman problem [17].

The initial MER design can be represented as a bit string. For example the MER design in Figure 4.16 can be represented as 111111111111111111. Removal of units 2,4,6,7 will transform this original string to 101010011111111111, by replacing the 1's by 0's at the appropriate positions. The GA starts with a random population of such arbitrary *strings* or '*chromosomes*'. Each chromosome represents a unique topology and has an associated cost which is calculated by solving the NLP deduced from the original MINLP.

GA consists of three operators

1. Reproduction
2. Cross-over; and
3. Mutation

Reproduction is an operator where an old string is copied into the new population according to that string's cost. Lower cost (ie. more fit) strings yield a higher number of offspring in the mating pool. It implements the survival-of-the-fittest by natural selection philosophy.

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[2] These are also known as 'schema' optimization procedures

During cross-over, chromosomes are mated by random selection from a fitness-modified population distribution function [59]. These mated chromosome pairs cross-over as follows: An integer position k along the string is selected uniformly at random in the interval $(1,l\text{-}1)$ (l is the bit string length). Two new strings are created by swapping all characters between 1 and k inclusively. The cost function for the new topologies is then evaluated. This is repeated for all the chromosomes in the mating pool.

Mutation is the occasional random alteration of a string position. For the code employed in this discussion, this simply means changing 1 to a 0 and vice versa. The last two operators have a certain probability associated with them.

Goldberg and Kuo [40] while combining pipeline systems, have reported that a near optimal solution can be easily reached within 100 generations. For a search space of 1.1×10^{12} approximately 3500 points where explored to find the optimal solution. This approach certainly looks promising and could even be used for total process plant synthesis for deriving a practical configuration from an initial superstructure which has all the solutions embedded in it as an alternative to the mathematical programming techniques proposed by Grossmann [13] for this problem.

7.4.2 Method of Simulated Annealing

Simulated annealing was first incorporated by Metropolis and co-workers [107] for the solution of a minimization problem. It is further described by Press et al. [125] and it has four elements:

1. A description of possible system configurations.
2. A generator of random changes in the configurations.
3. An objective function E (analogous to energy) to be minimized which is an ensemble property of the configuration.

4. A control parameter T (analogous to temperature) and an *annealing schedule* which tells how the control parameter is lowered from high to low values ie. after how many random changes in configuration each downward step in T is taken and how large that step is.

The method of simulated annealing is analogous with thermodynamics, specifically with the way that liquids freeze and crystallize or metals cool and anneal. A detailed description of the procedure is given by Press et al. The minimization procedure utilizes an analogue of the so-called Boltzmann probability distribution

$$Prob(E) \sim \exp\left(\frac{-E}{kT}\right) \tag{7.27}$$

In this equation k is the 'Boltzmann' constant which relates 'temperature' and 'energy'.

To implement this algorithm for heat exchanger unit reduction, an analogy between the heat exchanger network and the annealing procedure described above is required. A MER design gives the description of the possible system configurations. Units/matches can be removed/added at random. The objective function is the total network cost. The number of iterations is the control parameter and the number of units removed is the annealing schedule.

Steps 1 and 2 of this algorithm are similar to GA. Step 2 corresponds to the crossover and mutation procedures of GA. A combination of GA and simulated annealing could also be further investigated.

7.5 Dual Temperature Approach Design Method: Avenues for Further Research and Potential Applications

Chapter 5 presented a systematic method for the synthesis of HEN which feature an energy consumption greater than the minimum requirement. The network is represented by two parameters $\triangle t_{Emin}$ and $\triangle t_{Nmin}$. Given the value of these two parameters, methods are proposed for estimating the minimum number of shells, the minimum network area. Hence if the network costs can be estimated from these shell and area targets, the best combination of $\triangle t_{Emin}$ and $\triangle t_{Nmin}$ can be determined by a suitable optimization process.

7.5.1 Shell Target

The pseudo-pinch (see chapter 5) divides the stream system into two independent problem sets. Independent shell targets for each subproblem can be derived employing the method proposed in chapter 3. The total minimum number of shells required by the whole network will be the addition of the targets obtained for both subproblems.

7.5.2 Area Target

Three approaches are plausible. Each approach has excellent potential and each should be investigated in detail. A separate area target using the conventional formula of Townsend and Linnhoff [151] can be obtained for above and below pseudo-pinch point stream data which on combining will give the required target. Another approach is to use the composite curves, combined with the fact that the extra utility consumption α is cascaded down, as shown in Figure 7.10. The temperature of all the streams in a section can be modified depending on how α is distributed among all the streams. The area of each section can then be calculated by utilizing the "spaghetti" design.

An approximate target can also be obtained by the following observation

$$A_{\triangle t_{Emin}} > A_{\triangle t_{Emin}/\triangle t_{Nmin}} > A_{\triangle t_{Nmin}}$$

Hence,

$$A_{\triangle t_{Emin}/\triangle t_{Nmin}} = \frac{A_{\triangle t_{Emin}} + A_{\triangle t_{Nmin}}}{2} \tag{7.28}$$

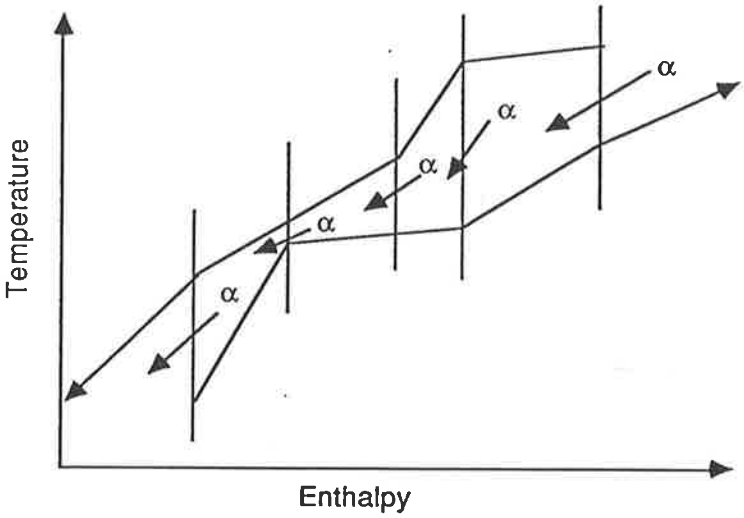


Figure 7.10: Heat cascade on the composite curves when extra α units of utilities are used

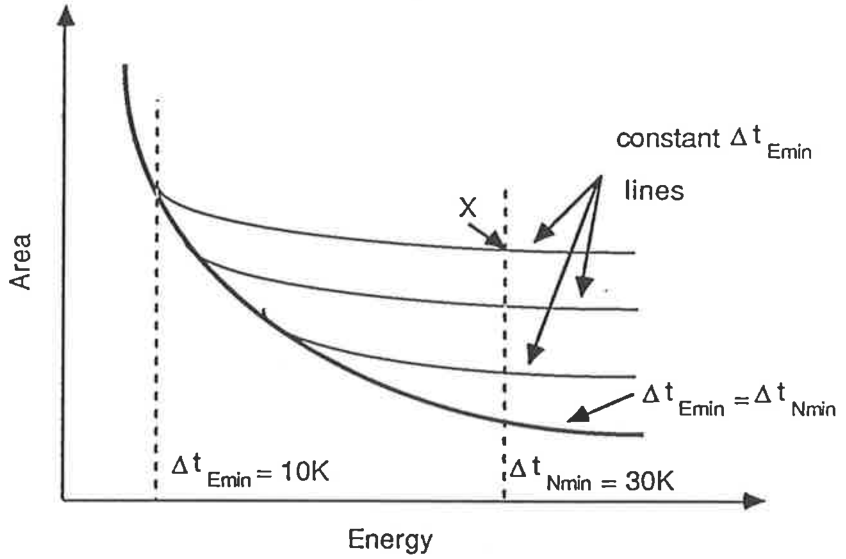


Figure 7.11: Area-energy curves using dual temperature approaches

where $A_{\Delta t_{Emin}}$, $A_{\Delta t_{Nmin}}$ are calculated using Townsend's formula [151]. A set of area-energy curves would now be obtained as illustrated in Figure 7.11. The point 'X' represents the minimum area of the network featuring $\Delta t_{Emin} = 10$ K and $\Delta t_{Nmin} =$ 30 K.

7.5.3 Best Value of Δt_{Emin} for a Given Value of Δt_{Nmin}

The basic aim of the dual temperature approach design method is to reduce the number of matches (units) and if possible the number of shells. Hence, an accurate method is required to estimate the number of shells in a unit. Bell's method is a good approximation for estimating the number of shells required in a unit. The analytical expressions for this method developed by Liu et al. [103] are as follows:

Let R be the heat capacity ratio and P be the thermal effectiveness defined as:

$$R = \frac{C_{p_c}}{C_{p_h}} \tag{7.29}$$

$$P = \frac{T_c^* - T_c}{T_h - T_c} \tag{7.30}$$

where T_c^* is the outlet temperature of the cold stream from an exchanger unit. Hence it can be shown that

$$N_{shell} = \frac{ln(\frac{1-P}{1-RP})}{lnR} \tag{7.31}$$

$$P = \frac{1 - R^{N_{shell}}}{1 - R^{N_{shell}+1}} \tag{7.32}$$

The above formulae are not valid when R = 1. For such a case,

$$\frac{RP}{1-RP} = \frac{T_h - T_h^*}{T_h^* - T_c} = R + R^2 + \ldots + R^{N_{shell}} \tag{7.33}$$

when R = 1,

$$\frac{P}{1-P} = N_{shell} \tag{7.34}$$

where T_h^* is the outlet temperature of the hot stream from an exchanger unit. From the above equations one can easily predict the number of shells required in a unit.

As discussed in chapter 5, from the energy targeting curve and the pinch temperature for $\triangle t_{Nmin}$, one can easily calculate the amount of heat that should be transferred across the pinch point by an individual stream so that a stream 'slips' and thus can reduce the target minimum number of units (refer chapter 5).

At times it may not be possible to reduce the number of units as stated above. However, using certain assumptions one can calculate the value of $\triangle t_{Emin}$ where the number of shells can change. A close look at the design method reveals that in the preliminary design normally only one match has an approach temperature

Table 7.5: Data for example 7.4

$\Delta t_{min} = 10$ K

Stream Number	C_p(kW/K)	T_s(°C)	T_t(°C)
1	3	60	180
2	2	180	40
3	2.6	30	130
4	4	150	40

of Δt_{Emin}. This match can be easily identified based on the C_p rule of the pinch design method. Thus, it is always possible to fix a likely match that would have an approach temperature of Δt_{Emin}. Hence the value of R is known. For this match, and for the corresponding value of Δt_{Nmin} the number of shells is given by equation(7.32). This will be the minimum number of shells required for this match. The value of N can be increased incrementally to get different values of P from which the value of Δt_{Emin} can be decided. This heuristic is used to concentrate a large number of shells in one unit assuming the shells in the rest of the units in the network will remain the same or decrease. Thus, with the above assumption we are locating regions in which the number of shells is likely to change. This will be illustrated by the following example the data for which is tabulated in Table 7.5.

Assuming $\Delta t_{Nmin} = 17$ K, the pinch point is determined by stream 4. Therefore the hot stream pseudo-pinch temperature is 150°C. A possible match of this stream below the pseudo-pinch point is with stream 1. For this match R = 0.75 and P = 0.81. The minimum number of shells for this match is two. Assuming that all

Table 7.6: $\triangle t_{Emin}$ targeting

N	Cold Pinch Temp.	$\triangle t_{Emin}$
2	133	17
3	136	14
4	140	10
5	143.5	6.5
6	145.4	4.6
7	147.64	3.33
10	149	1

the cold streams transfer the same amount of heat across the pinch point Table 7.6 details the likely values of $\triangle t_{Emin}$ which should be investigated for design.

7.5.4 Optimal Combination of $\triangle t_{Nmin}$ and $\triangle t_{Emin}$

For a given value of $\triangle t_{Nmin}$, the value of $\triangle t_{Emin}$ may be selected by the procedure outlined in the previous section. For these combinations shells, units and area targets can be independently predicted. Some simplifying assumptions may have to be made for combining these targets to calculate the actual cost. Optimal allocation of α also needs further investigation.

7.6 Retrofitting Heat Exchanger Networks

Retrofitting of an existing plant may be undertaken

- to save energy
- to increase throughput
- to overcome operability and maintenance problems

The following discussion focuses on the retrofitting of HEN with the aim of saving energy.

Recently, Tjoe and Linnhoff [149] and Jones et al. [66] have reported systematic procedures for retrofitting heat exchanger networks. Both have followed the same philosophy ie. set targets for payback period and then redesign the network.

Tjoe and Linnhoff use the area-energy curve for targeting. They draw a constant β curve on the area-energy plot to target for the payback period as illustrated in Figure 7.12. This target sets an economic global value of $\triangle t_{min}$ based on pay-back period. Cross pinch exchangers are removed and the network is redesigned using the pinch design method. The design obtained is then 'relaxed' to reduce the number of units.

The above targeting method does not account for the capital cost variations associated with the number of units removed and added. This is a serious drawback as, depending on the number of units removed and then subsequently added, discontinuities will be observed on the targeting curve. Furthermore, simplified cost equations are used for pay back period targeting. As pinch design rules are employed in the redesign of the network followed by further evolution by loop-breaking, topology traps identified in chapter 4 will exist.

Jones et al. have employed the dual temperature approach method. They "obtain a number of energy efficient grassroot networks from repeated runs covering a number

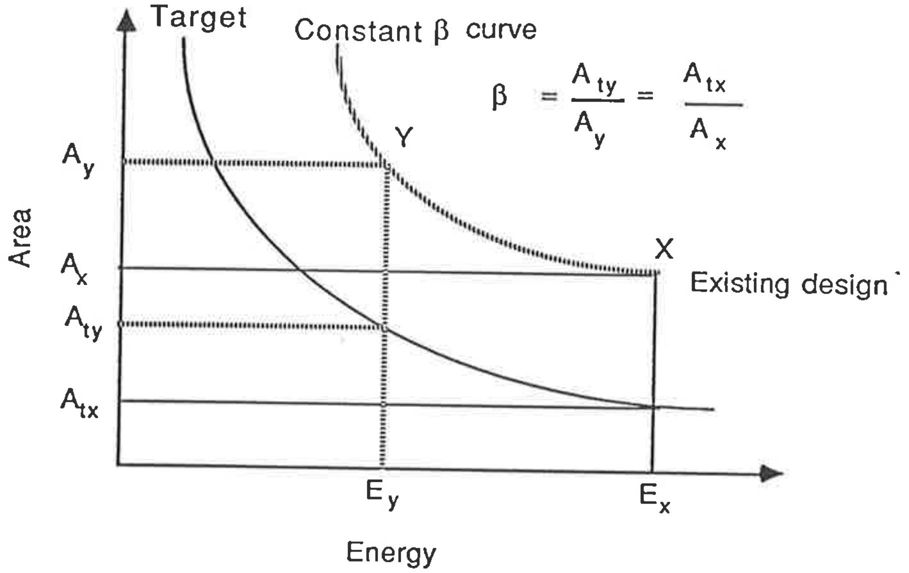


Figure 7.12: Retrofitting targeting with constant area-efficiency curve [149]

of temperature approaches" [149]. Tjoe and Linnhoff object to this approach and consider it to be fallible as it may miss better solutions. It is in the author's opinion that both these methods have this limitation. Furthermore, Tjoe and Linnhoff agree that their method is only good for small payback periods, where the area added is incremental. For higher payback periods, the method of Tjoe and Linnhoff could lead to non-optimal solutions. A new method is proposed which may lead to better targets and designs. The proposed design philosophy is similar to that of Tjoe and Linnhoff's design procedure, however, it uses the dual temperature approach as discussed in chapter 5.

7.6.1 Retrofit Targeting

Previously, a speculative method was proposed for area targeting when the dual temperature approach design method was used. The possible paths for retrofitting

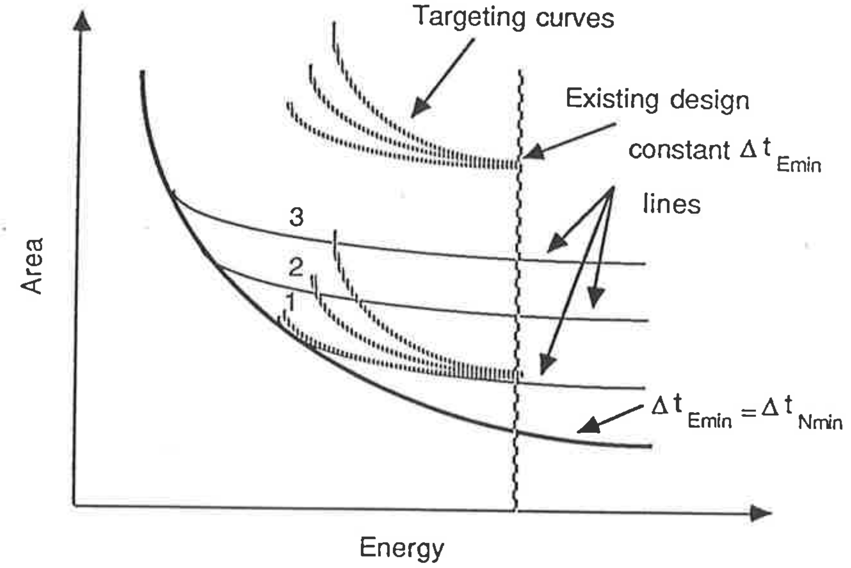


Figure 7.13: Retrofit targets using the dual temperature approach

are illustrated in Figure 7.13. The network that has to be retrofitted normally features a dual temperature approach. Two approaches can be employed. First, the network can have the same Δt_{Emin} as the original design (curve 1) and decrease Δt_{Nmin}. In the second approach, both Δt_{Emin} and Δt_{Nmin} are simultaneously decreased (curves 2 and 3). Thus, there will be a family of minimum area curves along which the network can be retrofitted. Actual targeting curves are generated by the *area efficiency* procedure [149]. The 'kinks' in these curves can be located by inspecting the network and identifying the exchangers that are "cross-pseudo-pinch" units.

7.6.2 Retrofit Design

Proper judgement and the designers interaction is required at this stage. The designer can assign appropriate values of α to the streams depending on the target

Table 7.7: α values of units in Figure 7.14

Unit	α
1	4
2	0
3	2
4	2.4
5	0.72
Total	9.12

values of $\triangle t_{Emin}$ and $\triangle t_{Nmin}$. Minimizing the number of units that are removed from the original design can be one of the criteria for assigning the value of α to individual streams. The method is illustrated by solving the problem reported by Tjoe and Linnhoff. The initial design is shown in Figure 7.14. They have predicted that a global $\triangle t_{min}$ of 26 K would have a payback period of 2 years. Four exchangers are removed and the final evolved design featured $\triangle t_{Emin} =$ 10 K and $\triangle t_{Nmin} =$ 26 K. The target value of $\triangle t_{Emin}$ and $\triangle t_{Nmin}$ predicted by Jones et al. for this problem is 20 K and 26 K respectively. The initial design features $\triangle t_{Emin} =$ 10 K on exchanger 5. Hence, the design procedure will be illustrated with $\triangle t_{Emin} =$ 10 K and $\triangle t_{Nmin} =$ 26 K. For these conditions the value of α is 5.52 kW. The original design had an α of 9.12 kW.

Each exchanger in the original design can be replaced by three exchangers, one above the pinch point, one below the pinch point, and one across the pinch point. The duty of the cross pinch exchanger is the heat load that the particular exchanger under consideration transfers across the pinch point. Such a split of exchanger 4 is illustrated in Figure 7.15. Table 7.7 shows the amount of heat transferred by each exchanger unit across the pinch point in the existing design.

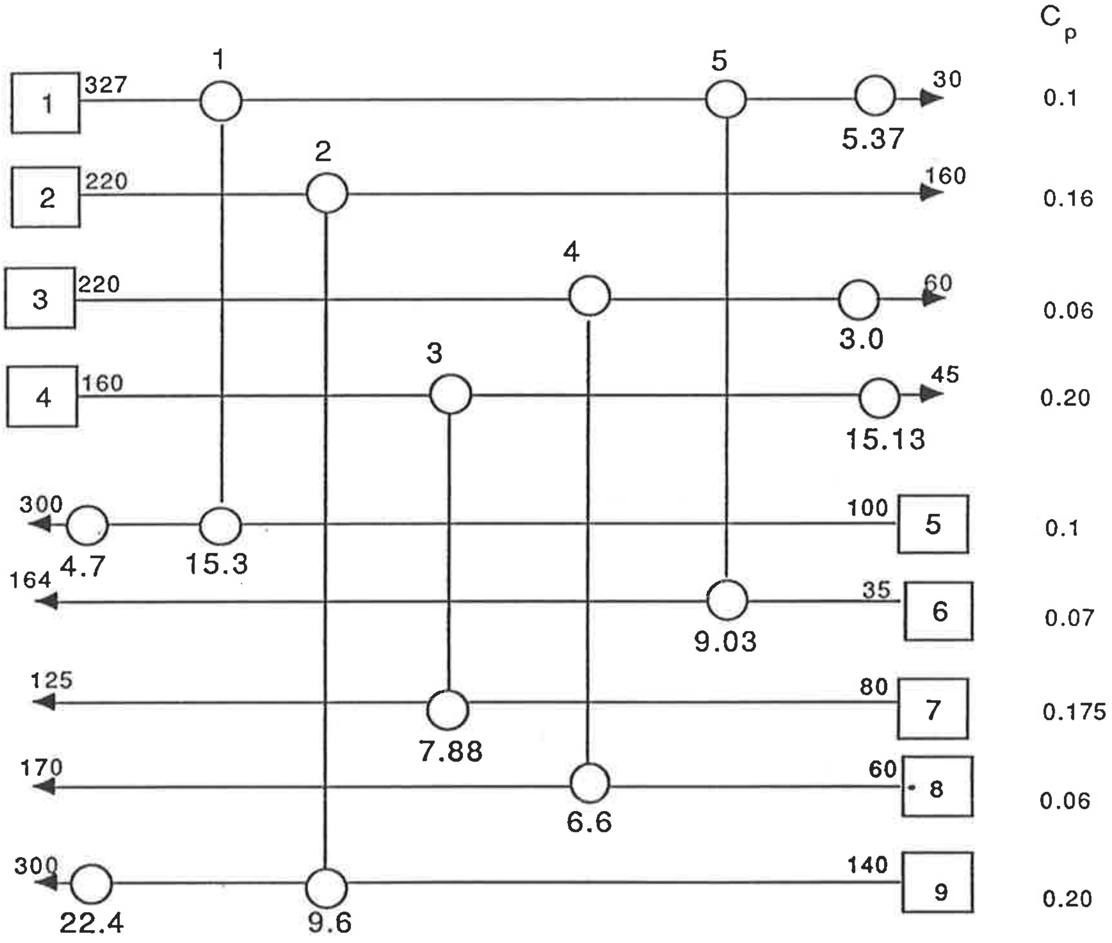


Figure 7.14: Existing aromatics network to be retrofitted [149]

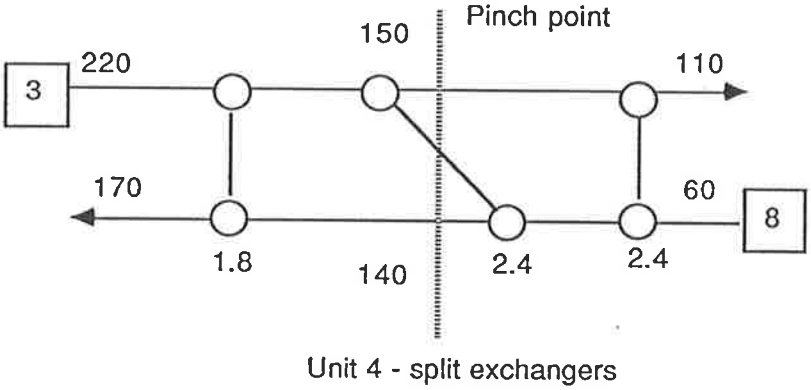


Figure 7.15: Calculation of the heat transferred across the pinch point by a cross-pinch exchanger

The retrofit design transfers 5.52 kW of heat across the pinch point. Depending on the units that are to be kept the designer can now remove the exchangers and fix the pseudo-pinch temperatures. In the existing design, units 2,3,4,5 cascade a total heat load of 5.12 kW. Thus, these exchangers need not be removed. An α of 0.4 kW can be assigned to hot stream 1 or cold stream 5. Assume that it is assigned to cold stream 5. Remove exchanger unit 1 from the original design. The pseudo-pinch temperatures are now fixed by the exchangers remaining from the original design and are detailed in Figure 7.16. The existing exchangers which are pseudo-pinch matches are placed first. Then the matches which are removed from the original design are given preference. Lastly, new matches are introduced. The final design obtained is the same as reported by previous authors [66,149].

This method has a distinct advantage over existing methods. Only one exchanger was removed from the original design as opposed to four exchanger matches removed by Tjoe and Linnhoff. The method of Jones et al. relies on a "black box" search, as the information which the problem "tells" is not exploited by them. The proposed method offers more flexibility in comparison with rigidity of Tjoe and Linnhoff's method. In this method the designer could have kept units 1,2,5 and allocated the residual α appropriately. This would have removed units 3 and 4 and an entirely

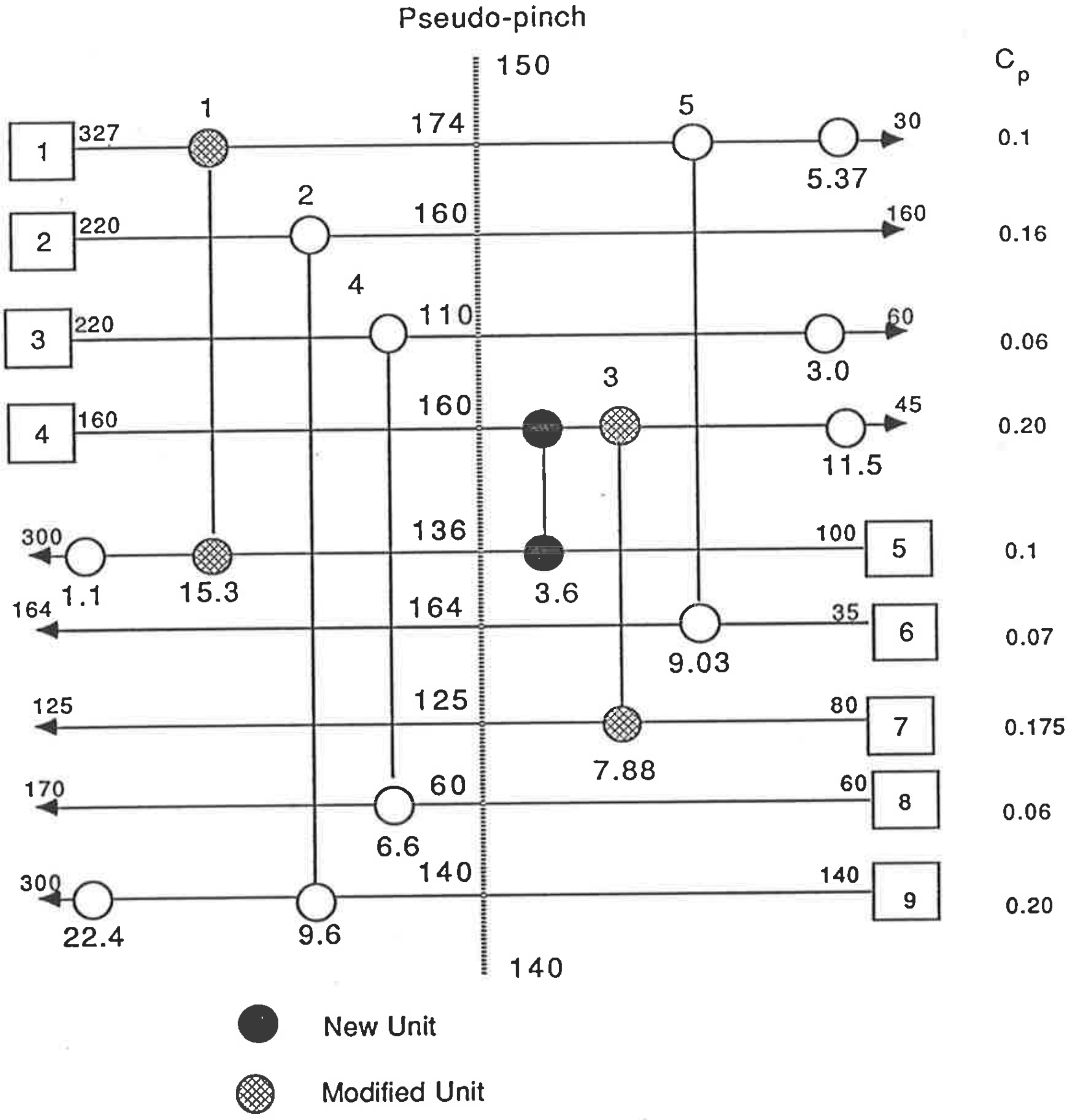


Figure 7.16: Retrofitted design

new topology which might have better operability characteristics could be evolved. Lastly, if the targets are accurate, the initial design requires no evolution. These distinct advantages in targeting as well as flexibility of the above method indicates that the designer has a better control of the retrofit procedure and certainly needs further development.

7.7 Total Process Plant Integration

Discovery of the pinch point and the three fundamental rules of pinch technology has led to the development of total plant integration. The main developments are in the field of heat and power integration, heat integration of distillation columns and sequencing etc. These procedures are based on the development of the process grand composite curve proposed by Townsend and Linnhoff [152] and Itoh et al. [63]. In deriving the grand composite curves they have assumed a global value of $\triangle t_{min}$ and that the associated heat exchanger network features maximum energy recovery corresponding to this $\triangle t_{min}$. However, as noted in this thesis, as well as the designs reported in literature, practical networks feature two different temperature approaches. The concept of pinch is no longer valid under such a situation. There is no pinch point (in the sense of representing minimum network $\triangle t_{min}$) in the actual network unless it is a MER design. Hence, total process plant integration should not be done using the pinch concept and the fallibility of this approach has not been reported in the literature todate. However, the methods developed are flawless for a MER network. Here modifications are suggested which require further investigation.

As noted in chapter 4, heat transfer across the pinch point led to cheap and elegant final designs. For optimal results the plant design and the network design should be carried out simultaneously.

7.7.1 Sink and Source Grand Composite Curves

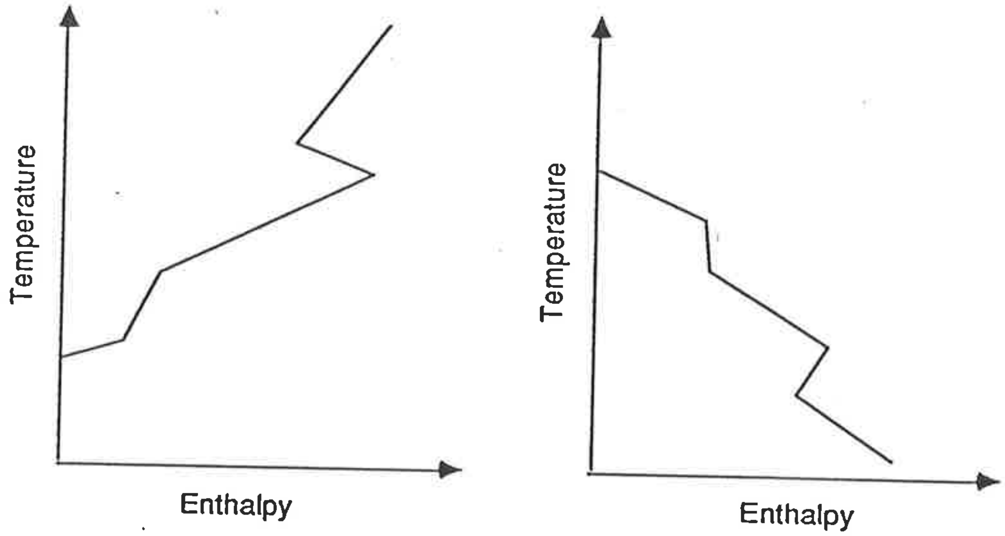
According to the pseudo-pinch approach any network can be divided into two subproblems. These subproblems can be designed and evolved without any constraint relaxation. Two sets of separate stream data can be generated for which independent networks can be generated. The network above pseudo-pinch point will require only hot utility and is referred as the 'sink' network. The network below pseudo-pinch point requires only cold utility and is referred to as the 'source' network. For each network a separate grand composite curve can be generated by using the procedure outlined by Townsend and Linnhoff [152]. For a hypothetical case these curves are illustrated in Figure 7.17. The superimposed curves are shown in Figure 7.17(c). Δt_{Emin} is used for generating these curves.

7.7.2 Multiple Utility Targeting

The procedure of Townsend and Linnhoff [151] can be used for targeting multiple utilities employing the sink/source grand composite curves. The advantage of the proposed method lies in the fact that certain opportunities missed by the existing method are identified. Firstly, lower temperature hot utilities can be used. Additionally, more stream can be generated as illustrated in Figure 7.18. Furthermore, the designer can fix the pseudo pinch temperatures in such a way that the furnaces can be operated with 100% efficiency [87] thus avoiding wastage of avaliable energy.

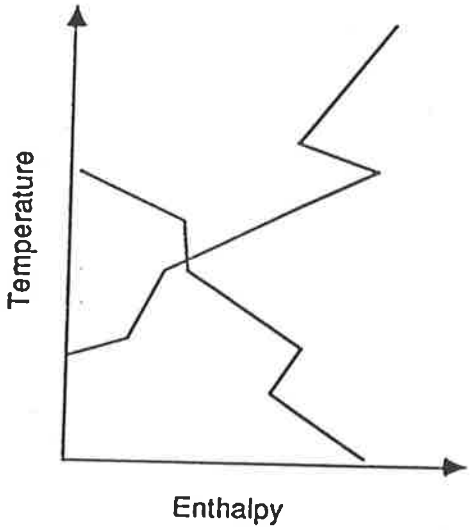
7.7.3 Heat and Power Integration

Systematic procedures for the placement of heat engines and heat pumps have been reported by Townsend and Linnhoff [152] and Colmenares and Seider [26]. In the case of the pseudo-pinch approach the principles are similar. The superimposed curves will be used to illustrate the appropriate placement of heat engines and heat pumps. Figure 7.19 illustrates the placement of a heat engine to achieve 100% efficiency. It is worth noting that the 'free-ride' obtained in one of the cases has not



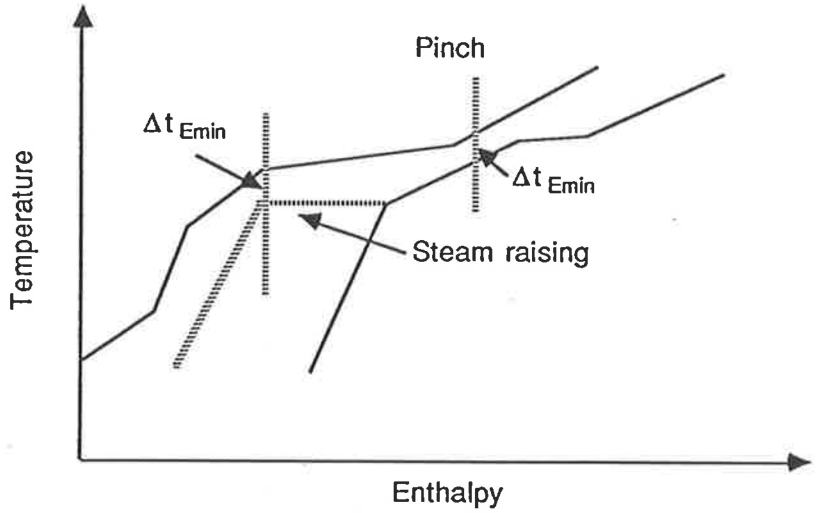
(a) 'Sink' grand composite curve.

(b) 'Source' grand composite curve.

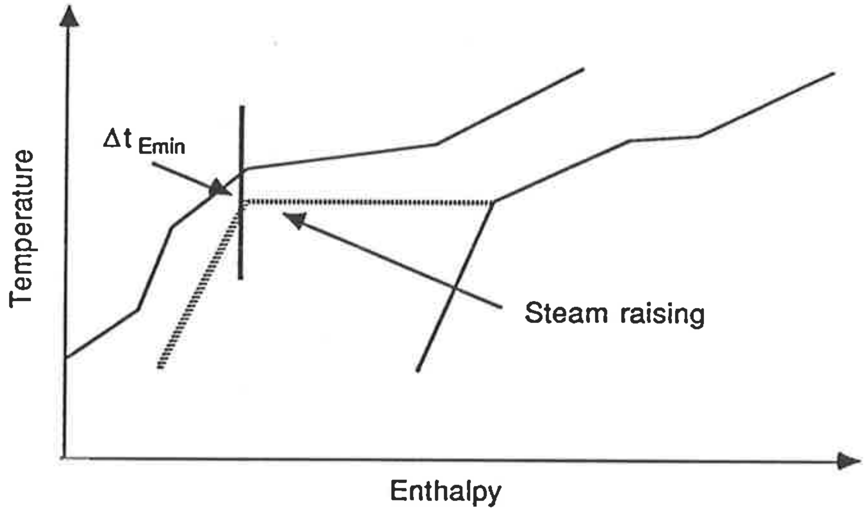


(c) Super imposed grand composite curves

Figure 7.17: Grand composite curves using the dual temperature approach



(a) Stream raising with single approach temperature.



(b) Extra steam raising using dual temperature approach.

Figure 7.18: Steam generation with different approaches

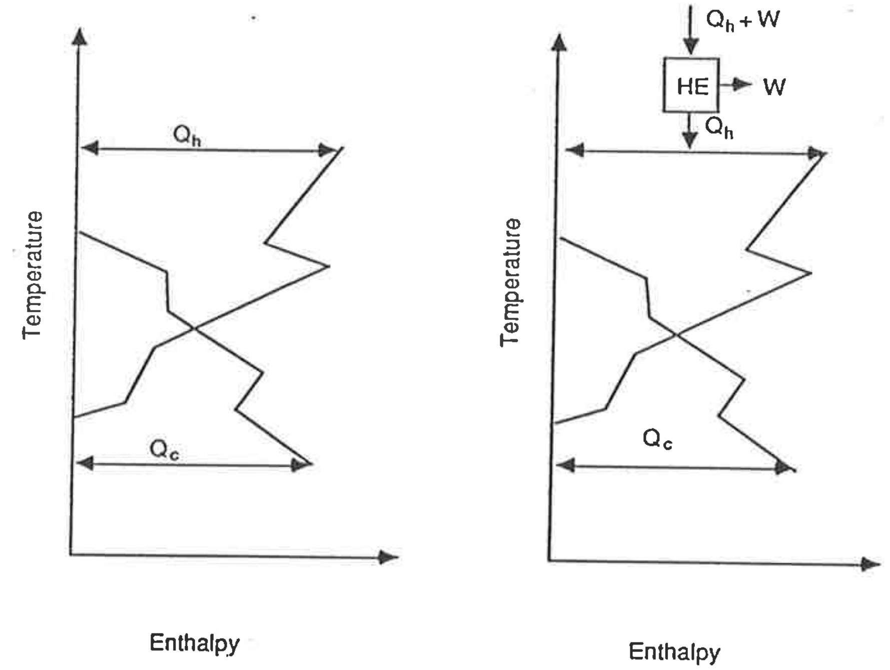
been reported in literature. The appropriate placement of a heat pump is illustrated in Figure 7.20. It should be placed so that it takes heat from the source network and transfers heat to the sink network. Placement of distillation columns is similar to heat engines.

The generation of the above profiles will also affect the selection of practical heat pumps and heat engines. These concepts need detailed investigation as it represents a practical situation. Especially the case when a heat engine or a distillation column is placed such that it takes heat from the source network and rejects it in the sink network. Work or separation would be achieved at absolutely no energy penalty!

7.8 Handling Designer Imposed Constraints

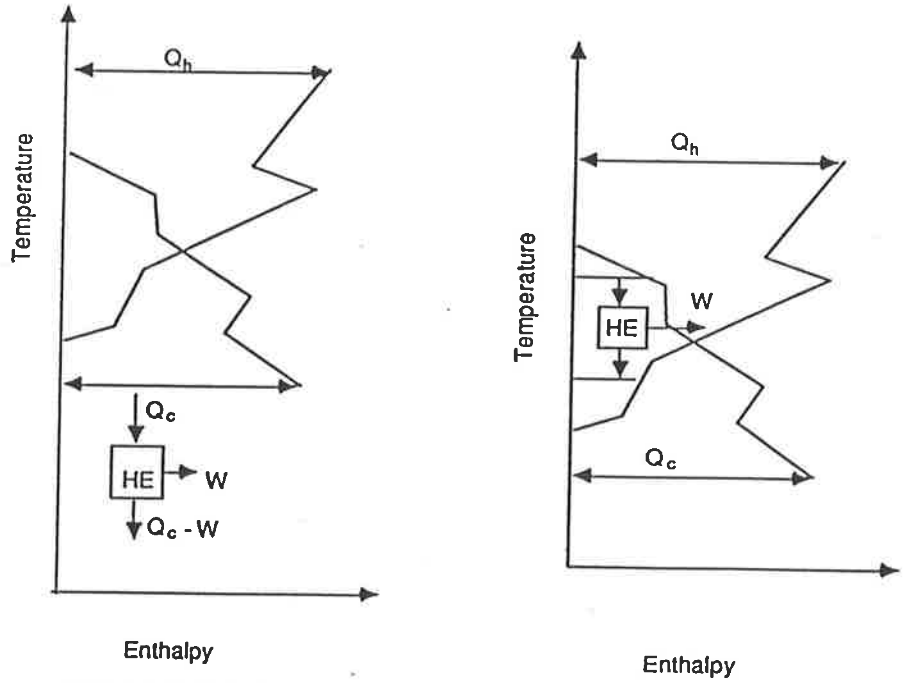
Chapter 6 proposed a method for handling designer imposed constraints based upon the insights obtained by solving a modified trans-shipment model. The network is divided into subproblems, where the number of constraints are changing, and then the network is sequentially designed from the cold end. The method is simple, effective, flexible and is easily implemented. It can readily identify multiple solutions and large problems are handled efficiently. However, a large number of subnetworks may have to be designed in order to obtain the final network for a highly constrained industrial network.

Here, more fundamental insights into the nature of heat exchange taking place in the constrained network are elaborated. These insights are then used to evolve a systematic method for the synthesis of constrained heat exchanger networks.



(a)

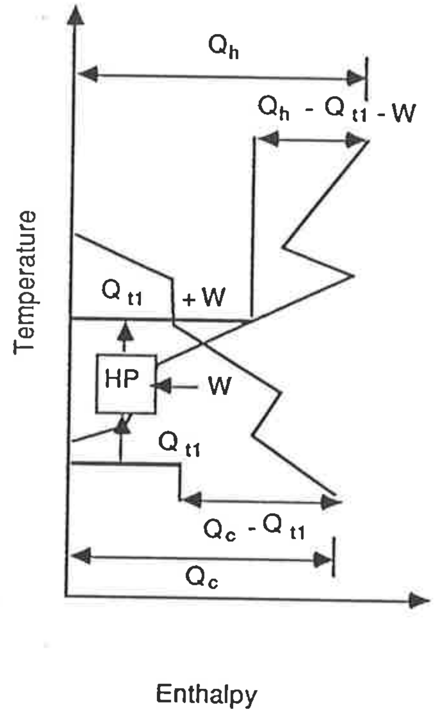
(b) Above 'sink' subnetwork.



(c) Below 'source' subnetwork.

(d) Free-ride.

Figure 7.19: Appropriate placement of heat engines using the dual temperature approach



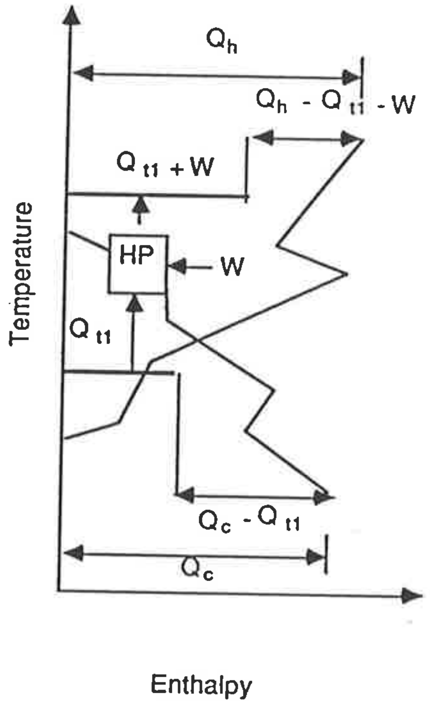


Figure 7.20: Appropriate placement of heat pumps using the dual temperature approach

7.9 Effect of Constraints on the Energy Consumption of the Network

The energy targets for a constrained network can be obtained by solving a transportation model or trans-shipment model of a linear program. These will be discussed in detail in the next section. First the factors contributing to the increase in energy consumption of a constrained network are discussed. The three major factors are:

- Number of constraints
- Type of constraints
- $\triangle t_{Nmin}$

7.10 Number of Constraints

Consider the data presented in Table 7.8 (with the assumed value of $\triangle t_{Nmin} = 10$ K). For the unconstrained case the hot utility requirement is 15400 kW. Should a match between stream 4 and stream 7 be prohibited, then the hot utility consumption increases to 16819 kW. This corresponds to an energy penalty of 1419 kW above that for the unconstrained case. Likewise, should another constraint be added, (for example match (1,7) is prohibited) then the energy penalty increases to 3032 kW. Thus, as the number of constraints increase the energy penalty is likely to increase.

7.10.1 Additivity

In the above example, if a match between stream 1 and stream 7 is the only prohibited match then the energy penalty is 675 kW. However, when this restriction is coupled with the additional constraint (match (4,7) prohibited) the energy penalty

Table 7.8: Data for example 7.5

$\triangle t_{min} = 10$ K

Stream Number	C_p(kW/K)	T_s(°C)	T_t(°C)
1	156.3	85	45
2	50.0	120	40
3	23.9	125	35
4	1250.0	56	46
5	1500.0	90	85
6	50.0	225	75
7	466.7	40	55
8	600.0	55	65
9	195.0	65	165
10	81.3	10	170

Constraints:(7,4),(7,1),(3,9),(5,9)

increases to 3032 kW. This penalty is greater than the sum of the energy penalties of individual constraints. Therefore, the total energy penalty resulting from a set of constraints is not additive. In general if α_k denotes the energy penalty associated with the k th constraint then the total penalty ($\alpha_{(1,2\ldots k)}$) is given by,

$$\alpha_{(1,2\ldots k)} \geq \sum_k \alpha_k \quad k = 1, 2 \ldots N_{constraint} \tag{7.35}$$

where, $N_{constraint}$ is the total number of individual constraints.

7.11 Types of Constraints

7.11.1 Key and Redundant Constraints

Consideration of the problem data of Table 7.8 demonstrates that the constraint (3,10) has no effect on the energy consumption. Whereas the constraint (1,7) and (4,7) have a significant effect. Clearly, some constraints are redundant. To understand this phenomenon consider the C_p table, for above and below pinch matches, tabulated in Table 7.9. The pinch point (56 - 46 ° C) is determined by hot stream 4 for $\Delta t_{min} =$ 10 K. It is evident from the C_p tables that the matches (1,7) and (4,7) are unavoidable as they constitute the pinch matches and no other alternative matches for streams 1 and 4 are possible. Hence, constraints of the type (1,7) and (4,7) are binding and will be identified as **key constraints.** Imposing key constraints will always result in an energy penalty. Forbidding (3,10) alone will not have any effect on the energy consumption of the network as it does not violate the C_p rule. Constraints of this type shall be referred to as **redundant constraints.**

Table 7.9: C_p table for example 7.5

(a) Above pinch $C_{ph} \leq C_{pc}$

Hot streams		Cold streams	
Stream Number	C_p(kW/K)	Stream Number	C_p (kW/K)
1	156.3	7	466.7
2	50.0	10	81.3
3	23.9		

(b) Below pinch $C_{ph} \geq C_{pc}$

Hot streams		Cold streams	
Stream Number	C_p(kW/K)	Stream Number	C_p (kW/K)
4	1250.0	7	466.7
1	156.3	10	81.3
2	50		
3	23.9		

7.11.2 Active and Passive Constraints

A characteristic of redundant constraints that demands careful attention is the synergistic effect of combinations of redundant constraints. In the present example, the constraints (1,10) and (4,10) are redundant constraints when considered individually and so are **passive** or **inactive** constraints. However, when they are considered simultaneously, both become active and the energy consumption will increase. A passive constraint will become active only in combination with its **complementary** constraint e.g. (1,10) and (4,10) are complementary constraints.

Detailed analysis of constraint types is important as the engineer can "assess" the relative importance of the constraints imposed. Identification of redundant constraints can dramatically reduce the search space and may aid in the identification of the different options for stream matching eg. careful application of stream splitting may be required to maximize energy recovery. As well, the characterization of constraints as 'active/passive' identifies complementary constraints which result in the increase of energy consumption of the network.

7.12 Effect of $\triangle t_{Nmin}$ on Constraints

As the value of $\triangle t_{Nmin}$ is increased the stream determining the pinch point changes. As well, streams may 'slip' through the pinch. Due to this the stream population above and below the pinch point will change. This has a significant impact on the type of constraint. Constraint (5,8) is not associated with an energy penalty when $\triangle t_{Nmin} =$ 10 K, for the data tabulated in Table 7.8. However, with an increase to $\triangle t_{Nmin} =$ 30 K this constraint changes type and results in an additional penalty α of 2381 kW. Here, stream 5 determines the pinch point and the match (5,8) is a pinch match and hence a key constraint. With $\triangle t_{Nmin} =$ 10 K, the match (5,8) is a redundant constraint as alternative matches for these two streams can be easily found. Such analysis is critical to the location of the optimum value of the $\triangle t_{Nmin}$ for constrained networks, as a kink will be observed on the constrained energy targeting plot for those values of $\triangle t_{Nmin}$ where redundant constraints become key constraints.

7.13 Minimum Energy Targets for Constrained Networks

For an unconstrained network four methods are used to compute the energy targets. They are:

- Composite curves
- Feasibility table analysis or Problem table analysis.
- Transportation model
- Trans-shipment model

Each of these techniques shall be discussed and if possible, they shall be modified to set the energy targets for the imposed set of constraints.

7.14 Constrained Composite Curves

Umeda et al. [154] proposed the use of composite curves to target for the minimum utility consumption. Their method is illustrated in Figure 7.21 for a four stream problem. Assuming no constraints the minimum hot and cold utility requirement can be determined by the 'overshoot' of the hot and cold composite curves. This target corresponds to the fact that 'vertical' heat transfer takes place in the network ie. any infinitesimal heat dQ transferred by a hot stream to a cold stream has a minimal exergy loss and consequently the resulting network features minimum area. As a consequence of this assumption, the individual stream temperature enthalpy curves can be combined into a single composite curve whenever they are in temperature contention. If a constraint is imposed, for example any match between stream B and stream D is prohibited, then the situation on the composite curves will be significantly altered. Consider the region on the composite curves where streams B and D are the only hot and cold streams. For minimum exergy loss, stream B will have to transfer all its heat to stream D. Unfortunately, this option is prohibited by the designer and an inevitable heat loss results, thereby increasing the hot utility. This could only be avoided by matching both the streams. Therefore, constraints may be associated with an inevitable exergy loss and analysis of the composite curves will fail to provide the energy target.

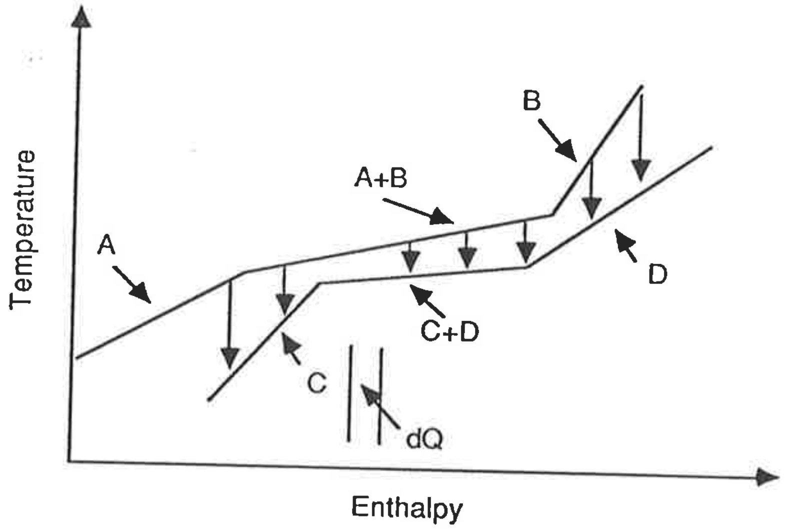
It should also be noted that the unconstrained composite curves predicting the same utility requirement as for the constrained case do not model the actual situation and hence cannot be employed in developing a minimum area target or a target for minimum number of shells. Futhermore, this also suggests that constrained networks do not possess a conventional thermodynamic pinch point but still possess a zero utility heat flow point as will be demonstrated in the following section.

These conclusions are only valid if the imposed constraints are active. For a redundant constraint, such as a prohibited match between stream A and stream D in Figure 7.21, the energy, area and shell targets can be obtained from the composite curves.

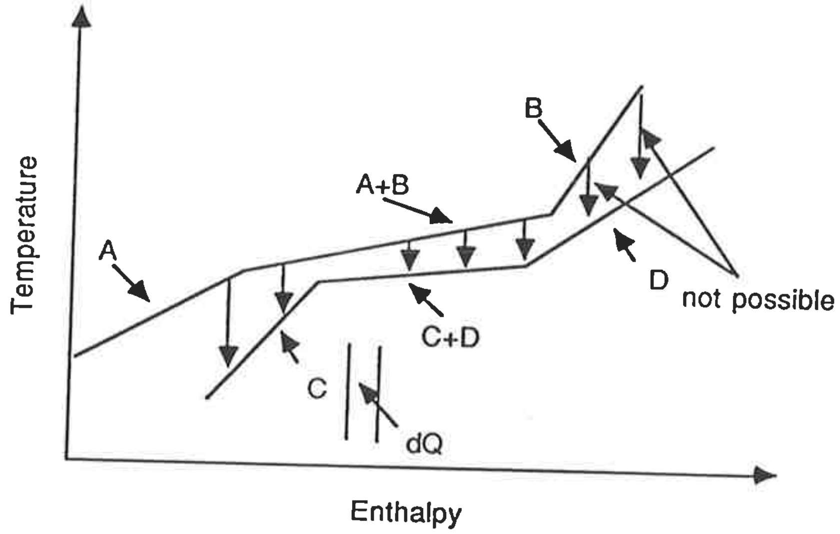
7.15 Temperature Interval Analysis

Before we develop a formal method by modifying the problem table analysis or the feasibility analysis of Hohmann [56], it is important to carry out a temperature interval analysis. This analysis has proved a valuable tool in comprehending the fundamental principles governing the synthesis of unconstrained HEN. Furthermore, it has also provided a tool for total process plant integration.

The temperature interval analysis will be illustrated by solving the problem data tabulated in the Table 7.8. The problem can be divided into a series of n subnetworks defined by temperature intervals. These intervals are obtained by the method



(a) Vertical heat transfer sets minimum utility targets without any stream matching constraints.



(b) Vertical heat transfer not possible when the constraint that streams B and D cannot be matched is imposed.

Figure 7.21: Composite curves not possible for imposed stream matching constraints

discussed in chapter 2. For the problems illustrated in the following section a global minimum approach temperature $\triangle t_{Nmin}$ will be assumed.

Each subnetwork will include a subset of streams of the original problem data and will represent a synthesis task with the imposed constraints. Unlike the unconstrained case, each subnetwork cannot be synthesized individually. This is because the decisions made in any subnetwork will interact the decisions to be made in the subsequent networks. The synthesis task of each subnetwork is considerably more difficult as the imposed matching constraints have to be accounted for. This suggests that the use of heuristic rules in designing each subnetwork should be explored. Such rules may be developed from the experience gained by solving problems but they often lack formal justification. However, the rules quoted in the following section have been proved to yield consistent energy targets for the problems reported in chapter 6.

7.15.1 Constrained Problem Table Analysis

The unconstrained problem table analysis was performed by dividing the stream system into temperature intervals. The same intervals can be used for the constrained case. In this case, individual networks are designed using the following heuristics:

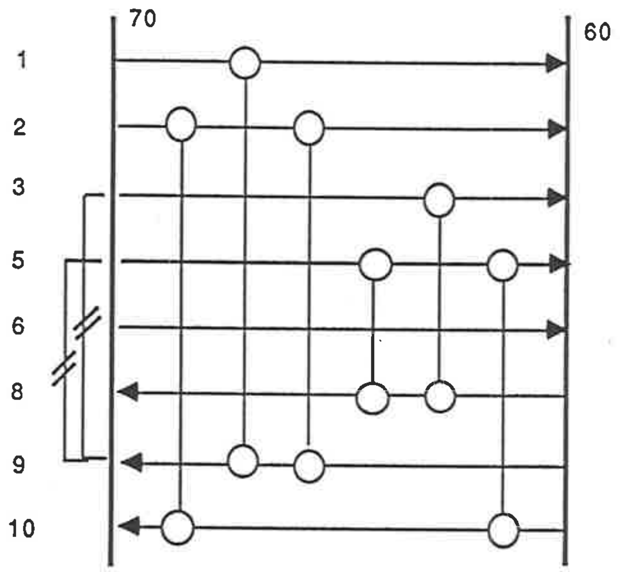
1. Start from the hot end subnetwork.
2. In this subnetwork, try to satisfy the cold stream having the minimum number of possible matches (NPM).
3. Match the selected cold stream with the hot stream having the maximum total number of constraints (TNC).
4. If TNC of some hot streams are the same, match the cold stream with the hot stream having the highest heat load in the interval.
5. If they have the same heat load then match the cold stream at random with the hot stream.

6. Repeat 2,3,4,5 till maximum possible heat is recovered.
7. Cascade the heat of the individual hot stream which did not reach subnetwork target temperature to the next adjacent subnetwork.
8. Satisfy the cold stream target temperatures by external utilities.
9. Repeat the above steps for all the subnetworks.

The application of these rules is illustrated in Figure 7.22 for the temperature interval 70 - 60° C. Stream 5 is not in the temperature interval under consideration and so its C_p is notionally set equal to zero. However, its heat is now represented as cascading from the interval above and so this stream is included in the current interval.

Heuristic 4 and 5 may prejudice the assignment of heat loads to matches and hence may lead to a fallible target. However, in such a situation the concept of maximum/minimum stream enthalpy cascading is suggested. According to this concept, the maximum and minimum amount of heat that can be cascaded by a stream depending on how the stream is matched in the subnetwork is calculated. Thus, associated with each stream there will be a maximum and minimum residual heat that is cascaded into the adjacent lower temperature subnetwork. This concept is not investigated in detail as it very difficult to code it, and furthermore, the information generated by the this exercise can be easily obtained by using mathematical programming methods such as the trans-shipment model [117].

Alternatively, energy targets can be obtained by solving the transportation model [20]. The transportation model only gives the targets and does not generate any extra information that can be employed for further development in design. The problem table analysis outlined above using the heuristic rules can be tedious, but it gives information about multiple solutions. Multiple solutions can also be found by successive reformulations of the trans-shipment model.



C_p	ΔH	R_{k-1}	ΔH_T	NPM	TNC	R_k
156.3	1563.0	0.0	1563.0	3	1	0.0
50.0	500.0	232.5	732.5	3	0	291.0
23.9	239.0	0.0	239.0	2	1	0.0
0.0	0.0	6519.5	6519.5	2	1	0.0
50.0	500.0	500.0	1000.0	3	0	1000.0
600.0	6000.0	0.0	6000.0	5		
195.0	1950.0	0.0	1950.0	3		
81.3	813.0	0.0	813.0	5		

Figure 7.22: Constrained temperature interval analysis

Table 7.10: Data for example 7.6

$\triangle t_{min} = 20$ K

Stream Number	C_p(kW/K)	T_s(°C)	T_t(°C)
1	7.032	160	110
2	8.44	249	138
3	11.816	227	106
4	5.6	271	146
5	9.144	96	160
6	7.296	116	217
7	18	140	250

Constraints:(1,6), (2,5), (3,6), (4,7)

7.16 Design of Constrained HEN (An Alternative Approach)

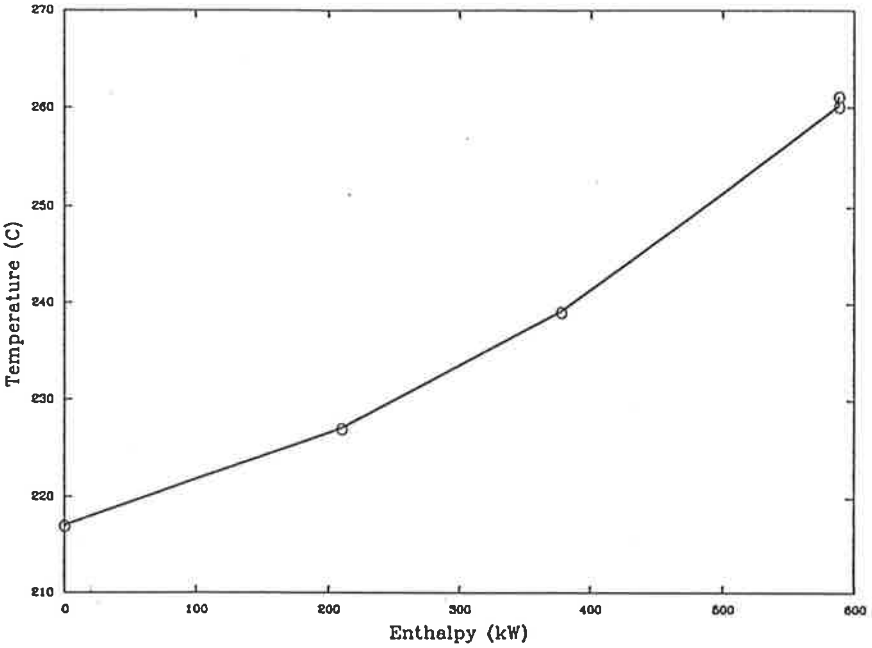
The subnetworks generated in the problem table analysis can be evolved using evolutionary rules discussed in chapter 2 and chapter 4. However, this could be a very tedious and lengthy procedure. The design method outlined in the previous chapter is effective, but if the number of constraints is large then a large number of subnetworks will have to be designed. To remove this limitation some modifications are needed. The problem table and the trans-shipment model give information about the total residual from each subnetwork and the total amount of hot utility used in each subnetwork. These can be plotted separately as illustrated in Figure 7.23 for the problem in Table 7.10.

The heat demand curve illustrates a point below which no heating utility would be required. This point is called the *constrained pinch point.* An unconstrained thermodynamic pinch point can also be identified in the usual way. The lowest temperature of the constrained and unconstrained pinch points, is called the *dominant pinch point.* For designing the network the constrained data should be divided at this dominant pinch point. The hot stream temperatures should be modified so that the streams actually cascade the heat residuals at this point as seen in Chapter 6. Matching is done by constructing a match tableau and is illustrated by the following example.

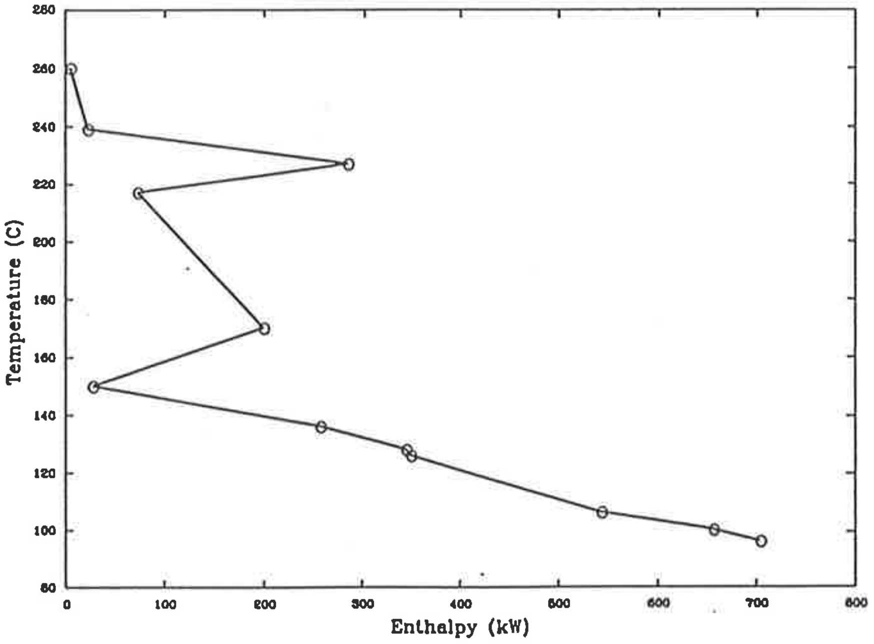
In the example considered above, the constrained pinch point occurs at 237 - 217 °C and the unconstrained pinch point is 160 - 140 °C. Hence, the stream system should be subdivided at the dominant pinch point 160 - 140°C. At this point stream 3 has a residual of 28.08 kW so its temperature at the dominant pinch point would be 162°C.

7.16.1 Feasible Match Analysis

A matrix representation will be used. The stream matching process is illustrated in Figure 7.24. The hot streams are the rows and the cold streams are the columns of the matrix. A'×' implies that a match between the two streams is not possible. 'R' indicates a restricted match. '$\surd$' indicates that a match may be possible. The rules outlined in chapter 5 should be employed to find all the possible matches. For the example under consideration, streams 2 and 3 can match with stream 7 only. Hence, stream 7 has to be split. The new matrix M-2 is obtained. Stream 7a represents the split stream. Now the hot stream 4 and cold stream 6 can be matched to "tick-off" stream 6. The resulting matrix M-3 is now used to decide the next match. A match between stream 4 and 5 is possible. Matrix M-4 indicates that a match between stream 2 and 7 is possible. The only possible match in matrix M-5 is between stream 3 and 7. This will be a forced match. Stream 5 can be satisfied by matching it with stream 3. Finally, stream 3 and 7 can be rematched. As all the hot streams have reached their target temperatures, hot utility will be used on stream 7. The



(a) Heat Demand Curve



(b) Heat Supply Curve

Figure 7.23: Heat demand and supply curves for example 7.6

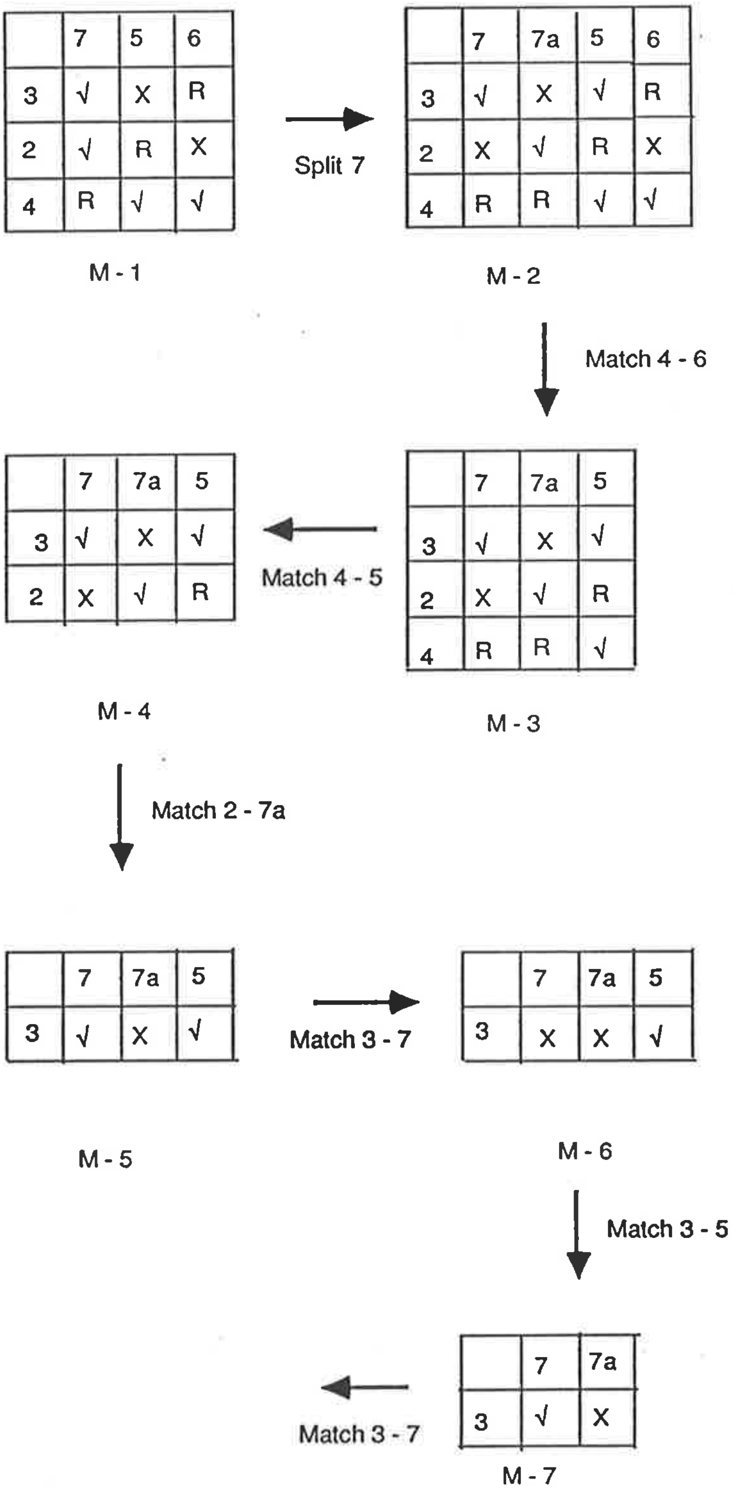
resultant above dominant pinch design is illustrated in Figure 7.25. Below dominant pinch design is illustrated in Figure 7.26 along with the feasible match analysis. The heuristic rules for constrained problem table analysis are used for conflict resolution and deciding the order of placing the matches. Multiple design topologies can be easily identified.

This example illustrates that the "ticking-off" heuristic should be used with caution and the normal pinch design method is invalid when considering designer imposed constraints. Furthermore, it also illustrates the complete control of the designer over the evolution of the network. It "tells" the options available and can make appropriate decisions based on the knowledge about the problem at hand. Preferences can be easily included.

7.17 Heat and Power Integration With Designer Imposed Constraints

The heat supply (HSC) and heat demand (HDC) curves illustrated in Figure 7.23 form the basis for heat and power integration with imposed constraints. The principles outlined by Townsend and Linnhoff [152] apply to the appropriate placement of heat engines, heat pumps and distillation columns. However, the actual placement is more complex than the unconstrained case. Figure 7.27 illustrates the appropriate placement of heat engines and distillation columns. A heat engine could also be placed such that heat is taken from the heat supply curve and rejected to the heat demand curve. Another approach for appropriate placement is illustrated in Figure 7.28 using the heat cascade diagram which may result in a 'free-ride'. Distillation columns can be placed similarly.

The above placement of heat engines suggests an option shown in Figure 7.29 in which indirect heat transfer takes place between the restricted hot and cold streams via another heat transfer medium. Two exchangers are used and hence may not be economical.



	7	5	6
3	√	X	R
2	√	R	X
4	R	√	√

M - 1

	7	7a	5	6
3	√	X	√	R
2	X	√	R	X
4	R	R	√	√

M - 2

	7	7a	5
3	√	X	√
2	X	√	R
4	R	R	√

M - 3

	7	7a	5
3	√	X	√
2	X	√	R

M - 4

	7	7a	5
3	√	X	√

M - 5

	7	7a	5
3	X	X	√

M - 6

	7	7a
3	√	X

M - 7

Figure 7.24: Feasible match analysis

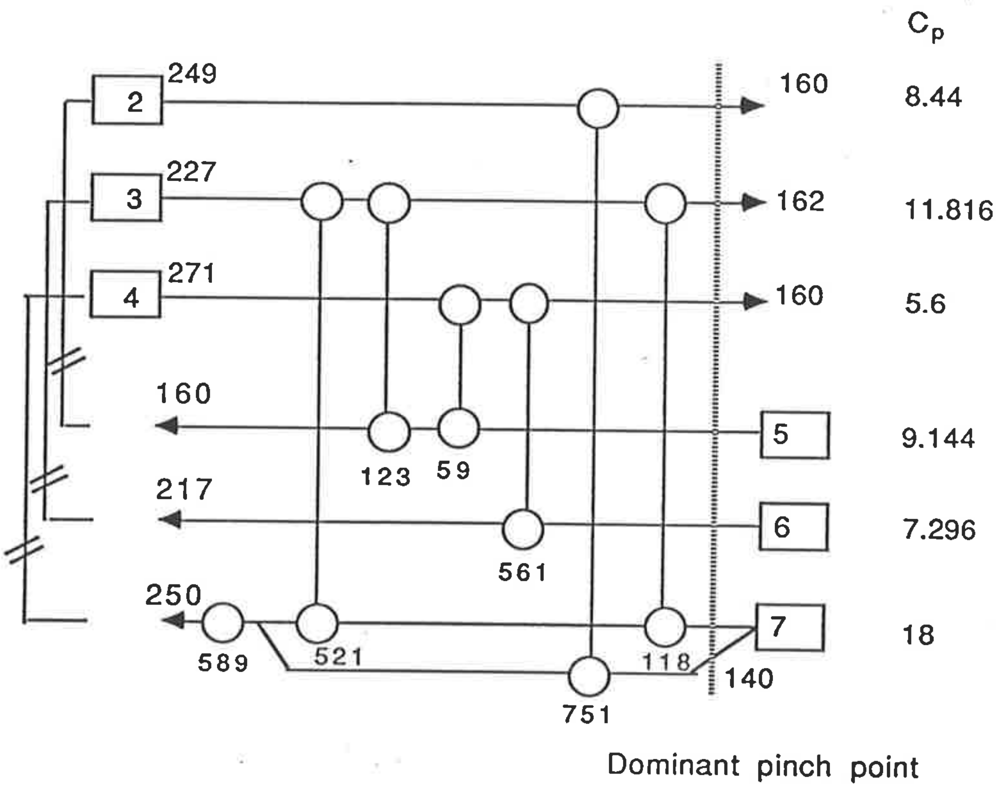
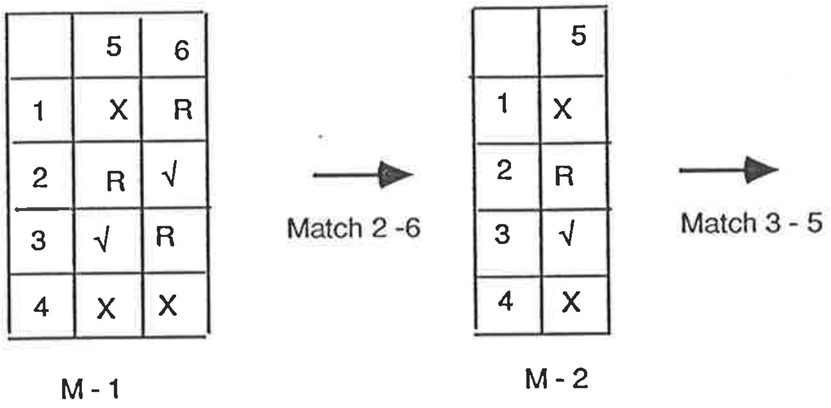


Figure 7.25: Above dominant pinch design for example 7.6



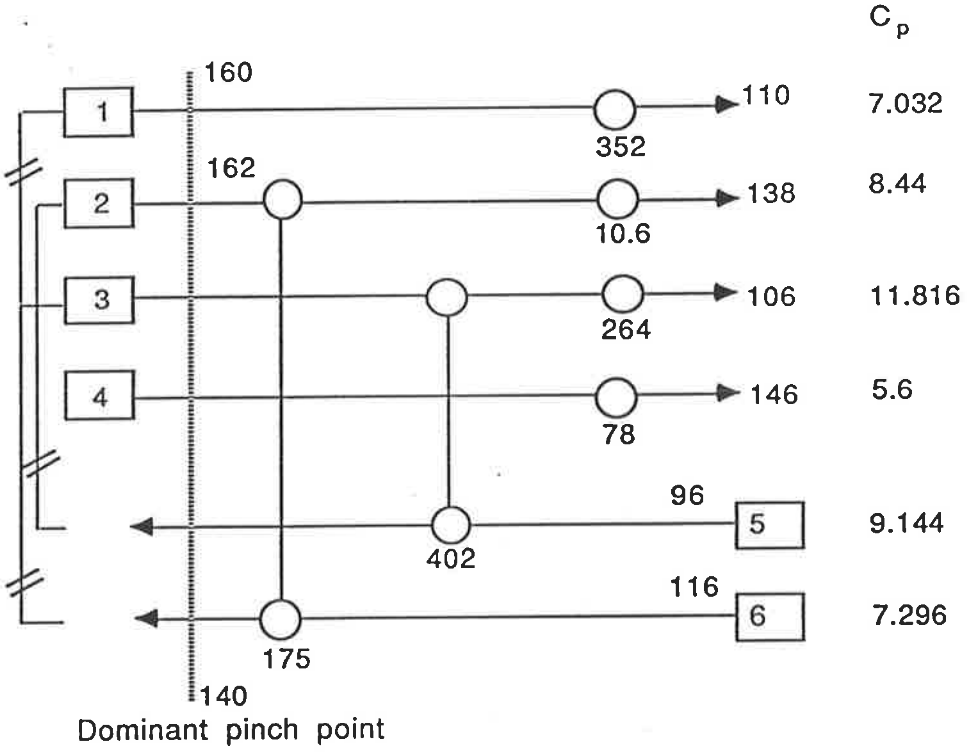
	5	6
1	X	R
2	R	√
3	√	R
4	X	X

M - 1

	5
1	X
2	R
3	√
4	X

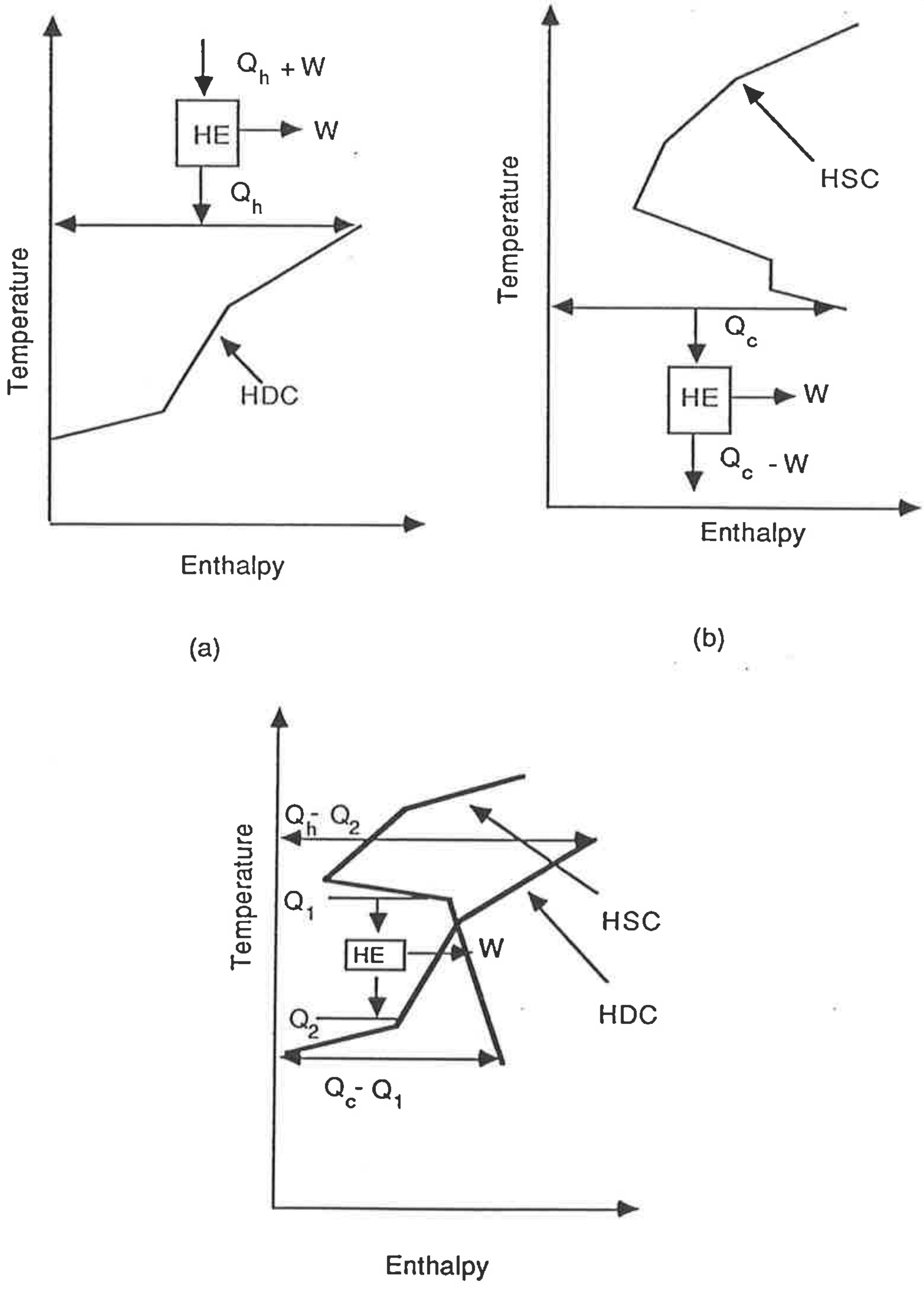
M - 2

(a) Feasible match analysis.



(b) Grid diagram.

Figure 7.26: Below dominant pinch design for example 7.6

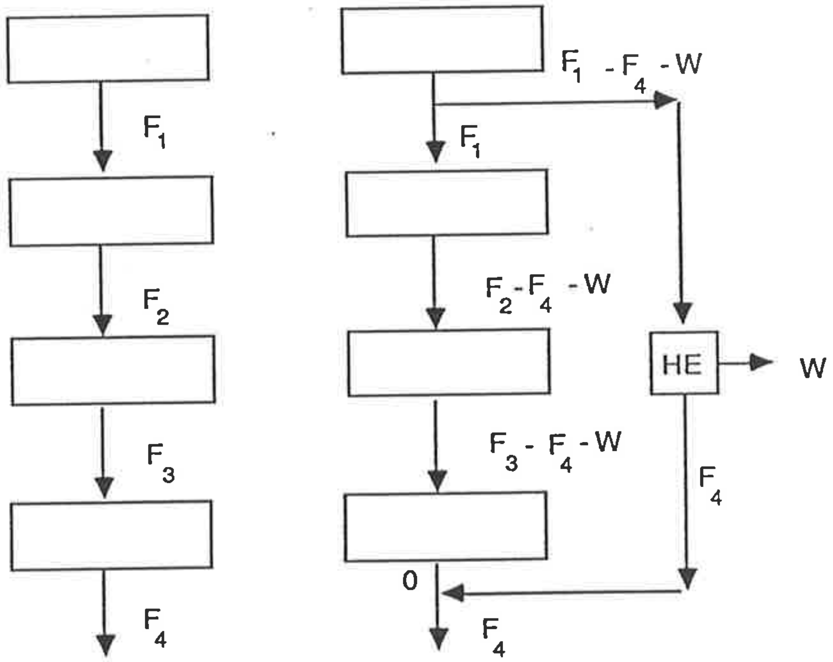


(a)

(b)

(c) Free ride

Figure 7.27: Appropriate placement of heat engines and distillation columns when the heat exchanger network has designer imposed constraints



(a) Unitegrated heat supply cascade.

(b) Free-ride with integration.

Figure 7.28: An alternative to conventional heat engine integration in the constrained heat exchanger network

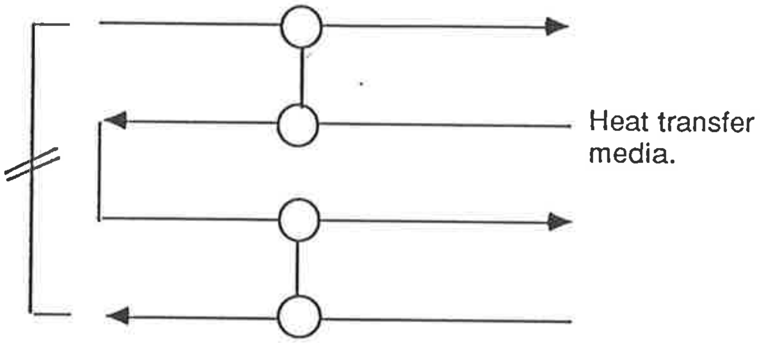


Figure 7.29: An indirect heat exchange for a prohibited match

The heat pump is said to be appropriately placed when it decreases the hot and cold utility requirement. It will have to be placed such that it takes heat from the heat supply curve at a lower temperature and transfers it to a higher temperature releasing its heat to the heat demand curve. This case is illustrated in Figure 7.30.

7.18 General Conclusions

This study has presented new concepts and methodologies for the synthesis of heat exchanger networks. The targeting approach first proposed by Hohmann and later exploited by Linnhoff and co-workers has proved to be very effective in the solution of complex HEN synthesis problems. The design philosophy of Masso and Rudd was employed for the synthesis and has also proved to be very effective. Fundamental understanding and analysis of the problem gives valuable insights, exploitation of

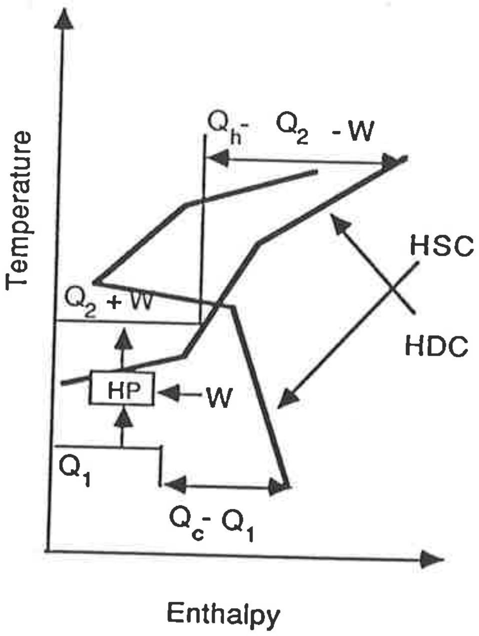


Figure 7.30: Appropriate placement of heat pumps in a constrained heat exchanger network

which gives simple design procedures leading to simple and elegant networks for practical heat integration problems.

The study of HEN synthesis is now a mature area and the concepts put forward in this chapter need to be further investigated. However, the rules and the approaches developed in this study are ideal for the development of an expert system. This will soon be a body of technology of considerable depth especially while considering practical constraints. The concepts put forward for total process plant integration are of considerable importance as they reflect real life situations. This in combination with the plausible retrofit design procedure could be employed to achieve simple and elegant overall process plant designs.

Appendix A

Cost Data

The following data was used for cost estimation in chapter 3.

Δt_{min} = 11.1 K for all problems.
Steam Temperature = 555 K for problem 4sp1.
= 508 K for rest of the problems
Latent Heat = 1527.25 kJ/kg for problem 4sp1.
= 1785.205 kJ/kg for rest of the problems.
Cooling water Temperature = 311 - 322 K
Heat Transfer Coefficient
Exchangers and Coolers = 0.8517 kW/(m^2 K).
Heaters = 1.1356 kW/(m^2 K).
Cooling Water Cost =1.1×10^{-4} \$/kg.
Steam Cost =2.2×10^{-3} \$/kg.
Cost coefficient = 1456
Cost exponent = 0.6
Rate of return = 0.1 for calculations in Table 4.1
= 0.4 for optimum Δt_{min} prediction computations
Operating time = 8500 hr/yr

The following data was used for costing the designs reported in chapter 5.

Energy Cost

Steam = \$ 50000/MW yr
Cooling Water = \$ 7500/MW yr
Steam temperature = 200°C
Cooling Water temperature = 12°C - 25°C

Plant Data

Rate of Return = 0.1
Lifetime = 5 years
Operating Time = 8000 hr/annum
Heat transfer coefficient of all streams = 1 kW/m^2 K

Cost Parameters

a = 1000; b = 0.6; m = 5000; n = 0.1; $\beta = 0.4$; $\gamma = 0.07$; $\phi = 0.2$ for tables 5.5, 5.6, and 5.8.

a=1; b=0.6; m=5; n=0.1; β=0.4; γ =0.07; ϕ=0.2; M=10 for figures 5.6, 5.18c, 5.23, 5.25 and E.1.

Appendix B

Number of Shells Required by an Exchanger Unit

A shell and tube exchanger may possess a number shells in series to meet the required performance. The number of shells required is dependent on the LMTD correction factor F_t. This factor is defined as the ratio of the actual mean driving force $\triangle T_m$ for any flow system to the best possible value for counter-current flow $\triangle T_{LM}$. If the exchanger is operated at too low a value of F_t, it falls in the region where large decrease in F_t occurs for a small difference in capacity ratio. This results in poor operability of the exchanger. To overcome this situation, often multiple shells are used for the same duty.

The value of F_t is fixed by the designer, who determines the tradeoff between $\triangle T_m$ and the exchanger cost. Normal design practice recommends a minimum value of F_t of about 0.8. " This criterion provides a reasonable value for TMEA E and J shells, but is too restrictive for units in series and multitube-pass cross flow ($F_{t_{min}}$ = 0.95), where larger F_t penalties can be tolerated and are economically justified. However, the best generalized recommendation that can be given is to use $F_{t_{min}}$ = 0.8. " [144].

Consider an exchanger unit shown in Figure B.1. The relationship for F_t can be

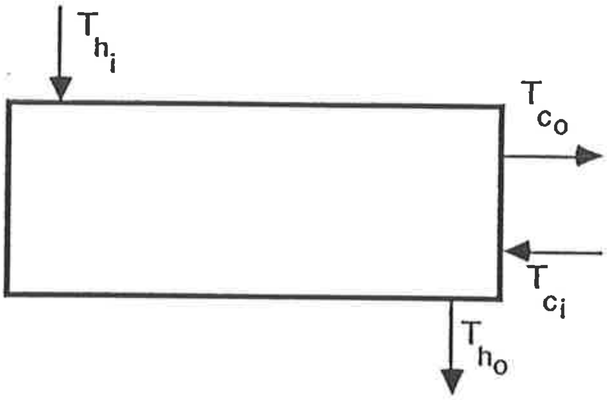


Figure B.1: A heat-exchanger unit

formulated by defining two parameters, R (heat capacity ratio) and P (thermal effectiveness).

$$R = \frac{T_{h_i} - T_{h_o}}{T_{c_o} - T_{c_i}} \tag{B.1}$$

$$P = \frac{T_{c_o} - T_{c_i}}{T_{h_i} - T_{c_i}} \tag{B.2}$$

Equation B.3, although only strictly correct for a 1-2 exchanger, is a reasonable approximation for all types of TEMA shells and flow arrangements [144].

$$F_t = \frac{\eta}{\delta \ln\{[2 - P(1 + R - \eta)]/[2 - P(1 + R + \eta)]\}} \tag{B.3}$$

where

$$\eta = \sqrt{R^2 + 1} \tag{B.4}$$

$$\delta = \left.\frac{R-1}{\ln(1-P)/(1-PR)}\right|_{R\neq 1} \tag{B.5}$$

$$\delta = \left.\frac{1-P}{P}\right|_{R\rightarrow 1} \tag{B.6}$$

Now, if $T_{h_o} = T_{c_o}$ then from equation B.1

$$T_{h_i} = (R+1)\times T_{c_o} - R\times T_{c_i} \tag{B.7}$$

Substituting this in equation B.2 we get,

$$P = \frac{1}{R+1} \tag{B.8}$$

Hence, F_t = f(R).

Figure B.2 is a plot of F_t values for different values of R for the condition stated above. It can be seen that the value of F_t is always greater than 0.8, for any value of R. This condition implies that no temperature cross occurs and only a single shell will be required for the unit. However, if the above condition was not satisfied then multiple shells should be required, for the reasons discussed above, with no temperature cross occurring in each shell. Thus, a single shell can be represented by the horizontal line on the composite curves in Figure 3.11. This simple graphical representation of the condition ensures that there will be no temperature cross. This construction was first suggested by Bell [12], without proof.

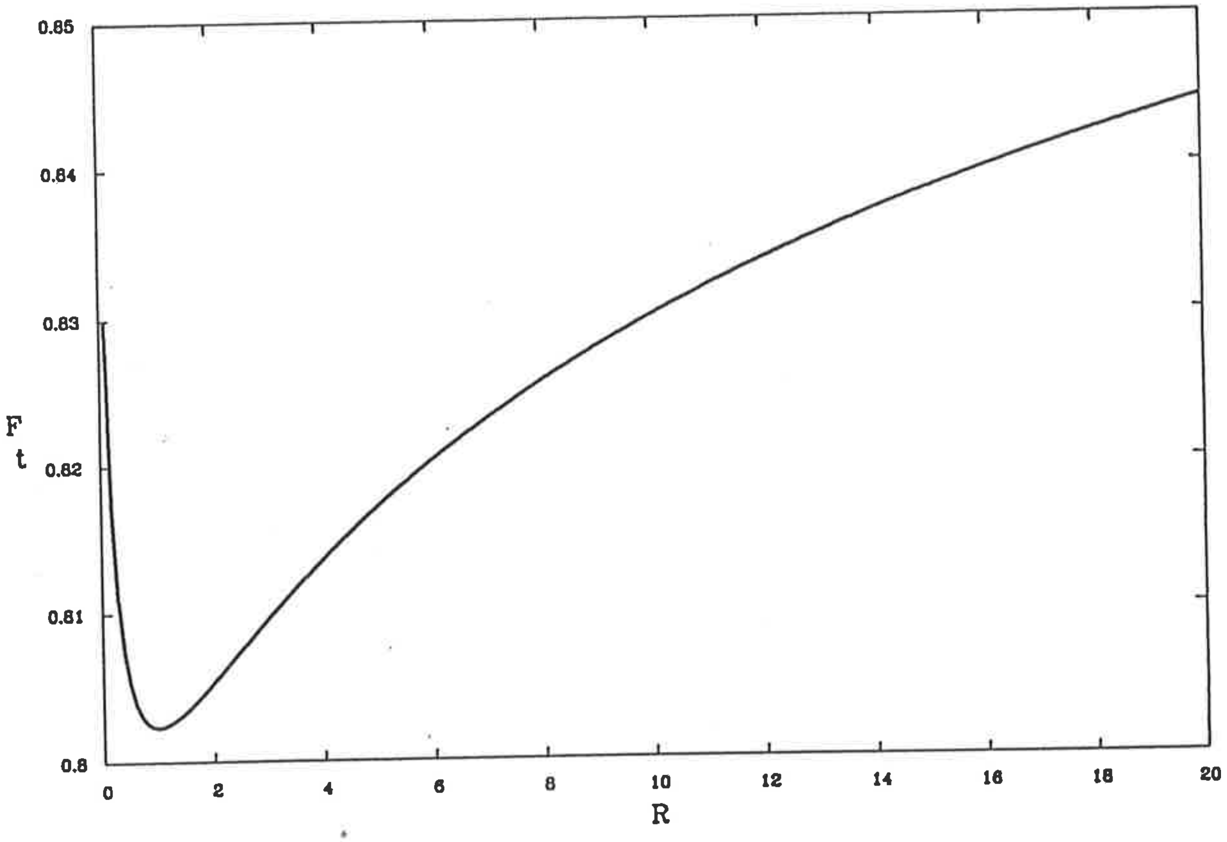


Figure B.2: Plot of F_t v/s R

Appendix C

Graph Theory

In this appendix some definitions and results in Graph Theory which are used in chapter 4 are listed. A *graph* is any collection of *points*, some of which are connected by *lines*. If a graph has p points and q lines then it is called a (p, q) *graph*. In heat exchanger networks the points correspond to the streams and the lines correspond to the heat exchanger units.

A graph is *acyclic* if it has no cycles or loops. A *tree* is a connected acyclic graph. A tree T is said to be a *spanning tree* of a connected graph G if T is a subgraph of G such that T contains all the points of G. For heat exchanger networks a spanning tree corresponds to a U_{min} topology. The lines of G not in a spanning tree are called *chords*.

Let us now consider a spanning tree T of a connected graph G. Adding any one chord to T will create exactly one loop. Such a loop, formed by adding a chord to a spanning tree, is called *fundamental loop*.

A graph G is *labeled* when the p points are distinguished from one another by names such as $v_1, v_2, \ldots, v_p$. Lines are represented by $x_1, x_2, \ldots, x_q$.

An *orientation* of a graph G is an assignment of a direction to each line of G. In heat exchanger networks the direction can be arbitrarily assigned as the direction of heat flow ie. from hot stream to cold stream, giving a *diagraph.*

C.1 Kirchhoff's Theorem

Let B be the $p \times q$ incidence matrix of an arbitrary orientation D of a given labeled graph G, so that the entry b_{ij} of B is +1 if the oriented line x_j is incident to the point v_i, -1 if x_j is incident from v_i, and 0 otherwise. Then the common cofactor of BB^T is the number of spanning trees of G [53].

Appendix D

Exergy Efficiency and Loop-Breaking

A thermodynamic analysis of the loops should give considerable insight into the process of loop breaking. The second law analysis of systems has developed the concept of exergy.

For flow systems, exergy is given by

$$\triangle Ex = \triangle H - T_0 \triangle S \tag{D.1}$$

where,

$\triangle Ex$ is the change in exergy flowrate

$\triangle H$ is the change in enthalpy flowrate

$\triangle S$ is the change in entropy flowrate

T_0 is the environmental temperature.

The change of exergy associated with a change in stream temperature from T_1 to T_2 is approximately [88] given by

Table D.1: Exergy analysis

(T_0 = 290 K)

	Unit	Heat Load (kW)	Efficiency ψ
Figure 4.2:			
	2	90	87.01
	4	30	19.5
Figure 4.4			
	2	15	88.82
	4	30	19.5

$$\triangle\, Ex = \triangle H \times [1 - (T_0/(T_2 - T_1)) \times ln(T_2/T_1)] \qquad \text{(D.2)}$$

The exergy efficiency of a heat exchanger is defined as [78,145]

$$\psi = \frac{\triangle Ex_{coldstream}}{\triangle Ex_{hotstream}} \qquad \text{(D.3)}$$

Referring back to the two MER networks in Figure 4.2 and Figure 4.4, an exergy analysis based on the exergy efficiency of the units in the loop is shown in Table D.1. From this table it can be noted that unit 4 in both cases has the lowest exergy efficiency. Previously, (Figure 4.3 and Figure 4.6) it was observed that removal of this unit incurred the smallest energy penalty. Hence it seems that the unit in a loop which has the lowest exergy efficiency should be removed so as to give the smallest energy penalty on network simplification. This provides a new, more soundly-based heuristic for the identification of a unit to be deleted from the network. However, it still lacks formal justification. Liapias and Walter [83] have also noted that " networks synthesized to minimize lost work (while satisfying approach temperature constraints) should incur minimum cost of utilities, since they will recover the maximum technically feasible amount of heat and cold."

Appendix E

Cost Equation

The major defect of previous cost formulations is the neglect of a number of important variables. These include:

- the recognition that units are composed of individual shells and capital and maintenance cost estimation should be based upon the area of individual shells.
- costs associated with network connections (e.g. pumps, pipe-runs, valves, tees associated with stream splits, etc.).

The traditional power-law expressions do include some local contribution for piping and it is extremely difficult to estimate pipework contribution reliably without any ideas of topology and layout in the initial stages of design. In his thesis, Linnhoff [88] proposed the following equation, correcting for the additional equipment cost and maintenance, but its use does not seem to have been cited for estimating the capital cost of heat exchanger networks.

$$\sum_{\text{Equipment}} \text{Annual Cost} = \left[1 + \frac{\beta(N_{pipes} + N_{nodes})}{4N_{unit}}\right]\left(\frac{1}{M} + \phi\right)\sum_{i=1}^{N_{unit}} C_i \qquad \text{(E.1)}$$

The equation includes a correction to the pipework cost $\beta[N_{nodes}/4N_{unit}]$ to account for network complexity introduced by stream splitting. This results from the implementation of the simple observation made by Linnhoff [88], namely: " *the number of pipe runs and junctions in a simple network is about four times the number of units*". ϕ is a maintenance factor and it corrects for the fact that complex networks require more maintenance than simple networks.

Again, this equation refers to units rather than the shells which constitute them. Obviously, a new improved cost equation is required to estimate the relative capital cost of different networks including those important features previously neglected.

As noted, the capital cost of a network, depends on the total area, number of units and shells over which it is distributed and the total pipe work required. Let us now outline the essential elements of a new cost function accounting for these variables.

1. Purchase cost

   The purchase cost C_s of the units (purchased as shells) required in the network can be calculated using equation(5.5) and applying it to individual shells rather than units.

$$C_s = \sum_{i=1}^{N_{unit}} \sum_{j=1}^{N_{shell}} aA_{ij}^b \tag{E.2}$$

   where A_{ij} is the area of the jth shell in the ith unit.

2. Installation cost

   Since units are usually made up of shells installed in vertically-aligned pairs, the installation cost C_I can be conveniently split into two contributions. Assuming the usual power-law dependence of cost on area and as each pair of installed shells only incurs one foundation cost, then

$$C_{Ieven} = 0.5 \left[\sum_{i=1}^{N_e} \sum_{j=1}^{N_{shell}} mA_{ij}^n \right] \tag{E.3}$$

   for those units $[1 \ldots N_e]$ where the number of shells is even, and

$$C_{Iodd} = \sum_{i=1}^{N_o} \left[0.5 \sum_{j=1}^{k-1} mA_{ij}^n + mA_{ik}^n \right] \tag{E.4}$$

for those units $[1 \ldots N_o]$ where the number of shells [= k] is odd

The total number of units:

$$N_{unit} = N_e + N_o \tag{E.5}$$

If in any shell the area A_{ij} is less than A_{min}, then the cost of installing this shell $[mA_{ij}^n]$ is replaced by $[mA_{min}^n + d]$ as discussed previously. The total installation cost is then calculated as

$$C_I = C_{Ieven} + C_{Iodd} \tag{E.6}$$

3. Piping and maintenance cost

To account for the additional piping costs incurred, when streams are split into parallel branches (requiring additional tees, controllers, etc.), we will utilize a modified form of the correction suggested by Linnhoff [88] and discussed previously. The additional cost C_{add} resulting from the stream-splits is:

$$C_{add} = \frac{\beta N_{pipes}}{4N_{unit}} + \beta \left[\frac{N_{nodes}}{U_{min}} \right]^{\gamma} \left(\frac{1}{M} + \phi \right) C_s \tag{E.7}$$

where C_s is the purchase cost as calculated in equation E.2 and N_{nodes} represents the number of splitting and mixing junctions. The first term accounts for the additional piping costs and the second term includes the amortization factor M and the maintenance charges ϕ. The second contribution in the first term is modified to $\beta \left(\frac{N_{nodes}}{U_{min}} \right)^{\gamma}$ to ensure that stream splitting does not become more attractive as the number of units increases. A pipework scale exponent γ is also included.

E.1 Overall Cost

The overall cost C_t may now be calculated by combining the three contributions to produce a more realistic formula for estimating the cost of the network.

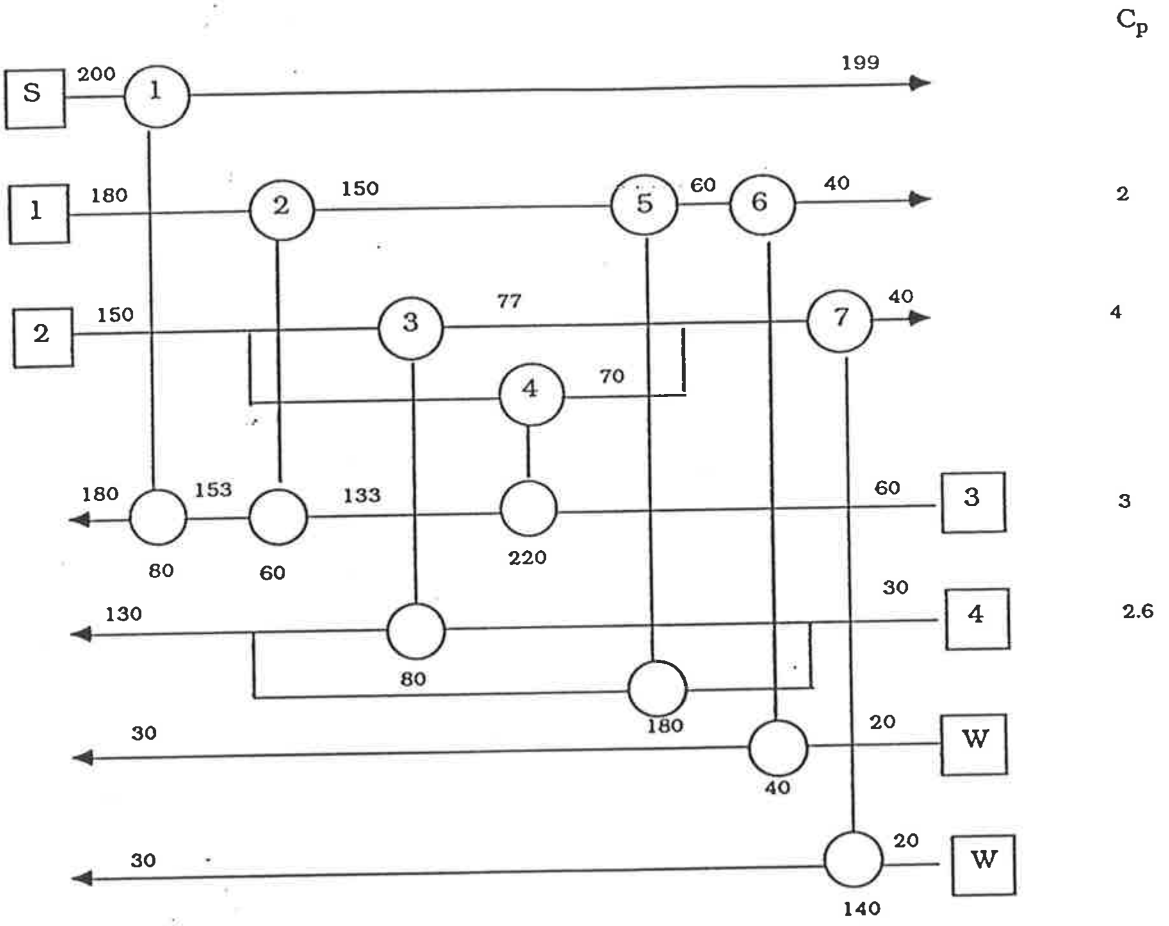
$$C_t = C_s + C_I + C_{add} \tag{E.8}$$

It is felt that the equation is more representative of the likely contributions to the total network cost. Whilst its absolute accuracy may be open to challenge, it should provide a reliable estimator of relative cost trends.

E.2 Illustration of capital cost estimation

Consider the network shown in Figure E.1. Details of the area and number of shells per unit are listed in Table E.1 along with the relevant cost data.

For this network, the capital cost of the whole network is 115.17 units.



Relative Capital Cost= 115.16.

Figure E.1: Example for cost estimation

Table E.1: Details of the network shown in Figure E.1

b = 0.4, a = 1, n = 0.1

$\gamma = 0.07$, b = 0.6, $\phi = 0.2$

M=10, m = 5

Code	N_{shells}	Heat Load kW	Area m^2	C_p \$	C_i \$
H3	1	80	5.15	2.67	5.87
E103	2	60	5.88	3.82	11.14
E204	4	80	6.23	5.22	41.81
E203	5	220	30	14.65	89.72
C2	1	140	7.04	3.22	6.08
E104	4	180	17.8	9.79	46.44
C1	1	40	2.37	1.69	5.45
Total				41.06	206.5

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