DESIGN OF CONSISTENTLY NEAR-OPTIMAL HEAT EXCHANGER NETWORKS BY A TWO-STAGE OPTIMISATION APPROACH

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Research in the field of Heat Exchanger Network Synthesis has been active as far back as 1965. Although the problem statement has remained essentially unchanged since then, numerous techniques have been developed to solve the heat exchange problem. Despite significant progress achieved over the years, a number of design issues remain unresolved or vaguely understood. Consequently, consistent generation of near-optimal heat exchanger networks is not guaranteed.

This project has therefore been undertaken to develop a flexible design technique that can be used to gain further insight into the nature of a heat exchanger network.

The objective of this project was to develop a network design technique that could be used to consistently generate networks that are near optimal. The main feature of the network design technique developed is the application of the optimisation process at two levels. The first level is match optimisation, and the second level is network optimisation. The objective function to be minimised is the total annual cost. The total annual cost is the sum of the annual cost of energy and the annual cost of capital. The annual cost of energy is the sum of the annual costs of hot utilities and cold utilities. The annual cost of capital is the sum of the annual costs of process, hot utility, and cold utility exchangers.

Match optimisation is the minimisation of the total match cost as a function of the minimum approach temperature. Using match optimisation, matches have been characterised with respect to energy recovery. In order to facilitate automation of the match optimisation process, matches have been classified on the basis of temperature and stream properties. The process of match optimisation allows for the consideration of economic factors and heat transfer factors in network design. The basis for the optimisation process is the trade-off between the annual cost of capital and the annual cost of energy.

Network optimisation is intended to minimise the annual cost of the network. It involves two main steps. The first step is match sequencing and the second step is evolutionary development.

The match sequencing process involves a preliminary step called stream arrangement. Stream arrangement is meant to give an insight into the likely stream pairing.

Depending on the relative positions of the streams on a temperature-enthalpy diagram, some streams may have to be fractured to form smaller independent streams. This is done to exercise control over the stream matching process. The objective is to achieve cost-effective energy recovery.

The process of match sequencing follows stream arrangement. The objective of the match-sequencing step is to select and match streams in an order that favours evolution of the preliminary network obtained into a near-optimal final structure. The technique should achieve this objective consistently. That is, for any given problem, use of the technique should result in a near-optimal final network.

The second step in network optimisation is evolutionary development of the preliminary structure that is a result of match sequencing. Before a network is evolved paths and loops are identified. The total annual cost of exchangers in a path or loop varies with energy distribution along the path or around the loop. So does the network annual cost. Therefore optimisation of paths and loops in a network can be performed to achieve a network cost reduction.

The technique has been evaluated by solving twenty-three case-study problems. Networks designed by this technique have been found to be comparable to designs obtained by different experts reported in the literature. However, due to the flexibility of this approach to network design there remains a wide scope for further development of the technique.

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Symbol(s)	Meaning
α	Hours of downtime
δ	Rate of return on investment
ΔH_h, ΔH_c	Heat load of the hot stream, and heat load of the cold stream, respectively
ΔH_{hi}, ΔH_{cj}	Heat load of hot stream i, and heat load of cold stream j, respectively
ΔH_s	Latent heat of steam
ΔT_{he}, ΔT_{ce}	Hot-end temperature difference, and cold-end temperature difference, respectively
ΔT_{LM}	Logarithmic mean temperature difference
ΔT_{min} or DT_{min}	Minimum approach temperature
ΔT_{opt} or DT_{opt}	Optimum minimum approach temperature
[Hi,Cj]	Match between the i^{th} process stream and the j^{th} process stream
A	Heat transfer surface area
A, B	Categories in match classification
ACT	Average Cost Target
Active-CU	Active cold utility
Active-HU	Active hot utility
APS	Actual percentage savings

Symbol(s)	Meaning
B1, B2	Two classes in match classification
B1-1, B1-2, B2-1, B2-2	Four divisions in match classification
B1-1.1 to B1-1.7, B1-2.1 to B1-2.6, B2-1.1 to B2-1.6, B2-2.1 to B2-2.7	Twenty-six cases of match configurations
C, C_a	Heat exchanger cost
C_0, C_1, b	Cost constants
C_{Ahu}, C_{Acu}	Annual capital cost of the hot utility, and that of the cold utility, respectively
C_{Ap}	Annual capital cost of the process exchanger
C_c	Sum of annual capital costs
$C_{ce,cu}$	Total annual cold utility cost
$C_{ce,hu}$	Total annual hot utility cost
C_e	Sum of annual energy costs
C_{hu}, C_{cu}	Unit cost of the hot utility, and unit cost of the cold utility
c_{ij}	Unit cost of match [Hi,Cj]
c_k	Heat capacity of the k^{th} stream

Symbol(s)	Meaning
$c_{min,cu}$	Smallest value of the match unit cost in the cold utility sub-matrix of the Selection Matrix
$c_{min,hu}$	Smallest value of the match unit cost in the hot utility sub-matrix of the Selection Matrix
$c_{min,p}$	Smallest value of the match unit cost in the process sub-matrix of the Selection Matrix
CRR	Cost Range Ratio
C_{tot}	Sum of capital costs and energy costs - the total annual cost
CTR	Cost Target Range
C_u	Unit cost of the utility which transfers (or receives) energy to (or from) a process stream
dc_{ij}	Difference between a given match unit cost and the smallest match unit cost in the sub-matrix of interest
dQ	Energy increment or decrement
EMAT	Exchanger minimum approach temperature
F_{cj}; F_{hi}	Heat capacity flowrate of cold stream j, and heat capacity flowrate of hot stream i, respectively
F_{cp}	Heat capacity flowrate
F_h, F_c	Heat capacity flowrate of the hot stream, and heat capacity flowrate of the cold stream, respectively

Symbol(s)	Meaning
h_h, h_c, h_{hu}, h_{cu}	Heat transfer coefficient of the hot process stream, the cold process stream, the hot utility stream, and the cold utility stream, respectively
Hi, Cj	The i^{th} process stream and the j^{th} process stream
HRAT	Heat recovery approach temperature
i, j, k	Running integers
L	Life time of a piece of equipment
LCB	Lower Cost Bound
N	Sum of the number of process streams, the number of hot utilities used, and the number of cold utilities used
NC	Network cost
NCR	Network Cost Range
$n_{c,high}$	Number of cold streams whose target temperature is higher than the highest hot stream supply temperature
$n_{cu,max}$	Maximum number of cold utility exchangers
n_h, n_c, n_{hu}, n_{cu}	Number of hot process streams, cold process streams, hot utility streams, and cold utility streams, respectively
$n_{h,low}$	Number of hot streams whose target temperature is lower than the lowest cold stream supply temperature
N_{hens}	Number of networks

Symbol(s)	Meaning
$n_{hu,max}$	Maximum number of hot utility exchangers
NPI	Network Performance Index
$n_{p,max}$	Maximum number of process exchangers
n_p	Number of process streams
O	Number of loops in a network
P_r	Percent energy recovery
p_s	Pressure of steam
Q	Energy exchanged
Q''_r	Heat flux of the process exchanger
Q_{acc}	Accessible energy
$Q_{acc,c}$	Accessible energy to the cold process streams
$Q_{acc,h}$	Accessible energy from the hot process streams
$Q_{c\text{-}high}$	Cold utility requirement in the high temperature range
$Q_{c\text{-}low}$	Cold utility requirement in the low temperature range
Q_{cu}	Energy transferred from a hot process stream to a cold utility
$Q_{h,abs}$; $Q_{c,abs}$	Absolute hot utility requirement, and absolute cold utility requirement, respectively
$Q_{h,min}$; $Q_{c,min}$	Minimum hot utility requirement, and minimum cold utility requirement, respectively

Symbol(s)	Meaning
$Q_{h\text{-}high}$	Hot utility requirement in the high temperature range
$Q_{h\text{-}low}$	Hot utility requirement in the low temperature range
Q_{hu}	Energy transferred from a hot utility to a cold process stream
Q_r	Energy recovered in a match
Q_{rec}	Recoverable energy
S	Number of independent sub-networks
T_{cjs}	Supply temperature of cold stream j which has a target temperature that is higher than the highest hot stream supply temperature
$T_{cjs,min}$	Supply temperature of the cold stream j which has the lowest supply temperature
$T_{cjt,high}$	Target temperature of the cold stream j whose target temperature is higher than the highest hot stream supply temperature
$T_{cu\text{-}in}$	Input or supply temperature of the cold utility stream
$T_{cu\text{-}out}$	Output or target temperature of the cold utility stream
T_{hi}, T_{ci}	Exchanger inlet and outlet temperatures of the hot and the cold streams, respectively
T_{his}	Supply temperature of the hot stream i which has a target temperature that is lower than the lowest cold stream supply temperature
$T_{his,max}$	Highest hot stream supply temperature

Symbol(s)	**Meaning**
$T_{hit,low}$	Target temperature of the hot stream i whose target temperature is lower than the lowest cold stream supply temperature
T_{ho}, T_{co}	Exchanger outlet temperatures of the hot and the cold streams, respectively
T_{hs}, T_{cs}	Supply temperature of the hot, and the cold streams
T_{ht}, T_{ct}	Target temperature of the hot, and the cold streams
T_{hu}	Temperature of the hot utility stream
TCSHL	Total Cold Stream Heat Load
THSHL	Total Hot Stream Heat Load
U	Overall heat transfer coefficient
UCB	Upper Cost Bound
u_{min}	Minimum number of units
U_p, U_{hu}, U_{cu}	Average overall heat transfer coefficient for heat exchange between a process stream and a process stream, a hot utility stream, and a cold utility stream, respectively
w_k	Flowrate of the k^{th} stream

Subscripts

Symbol(s)	Meaning
h	Hot process stream
c	Cold process stream
hu	Hot utility stream
cu	Cold utility stream
p	Process stream
A	Heat transfer surface area

CHAPTER 1

Introduction

1.1 Background to the Investigation

Energy transfer is an integral part of chemical processes. In order to maintain the required product quality and throughput the different process streams have to be at the correct temperatures and flowrates. These conditions of temperature and flowrate are specified at the design stage.

The design of energy-efficient processes has been the subject of research for more than thirty years. Two examples of such research activities are the synthesis of heat exchanger networks, and the synthesis of distillation-based separation processes. Both of these processes are industrially significant because they may involve large amounts of energy, and therefore significant operating costs. The investigation carried out in this project was concerned with the design of heat exchanger networks.

The synthesis of networks of process exchangers, heaters and coolers involves the transfer of energy from a set of streams that require cooling, called hot streams, to another set of streams that require heating, called cold streams. The major costs involved in this process are the cost of capital and the cost of energy. There is a trade-off between the cost of capital and the cost of energy. This means that if the energy exchange between hot process streams and cold process streams (energy recovery) increases then the energy exchange between process streams and utility streams (energy consumption) decreases. Thus, increasing energy recovery can decrease energy consumption. An increase in energy recovery implies an increase in the heat transfer surface area, and hence, an increase in the annual capital cost.

In the past, network designers aimed at maximising energy recovery. That practice can be justifiable if the capital equipment is cheap and energy is expensive. If the capital equipment is expensive and the energy is cheap the temptation might be to minimise energy recovery. The current trend is to minimise the sum of the annual cost of capital and the annual cost of energy, or simply, the total network cost.

The total network cost is a multi-variable function of the annual cost of capital and the annual cost of energy. Each of the annual cost of capital and the annual cost of energy is, in turn, a multi-variable function of the process conditions, individual stream properties, and the economies of scale.

An important feature of network synthesis is the existence of many possible network designs that can be generated for a given set of streams, process conditions, energy costs, and exchanger costs. The way streams are arranged in a network determines the network cost. The selection of the streams that exchange energy, and the order in which these streams are placed in a network, have a direct impact on the network cost.

The design stage of a heat exchanger network has long-term cost implications. Once commissioned, a network structure consumes energy on a daily basis. If the network design is inefficient an extra cost is incurred on capital equipment, and energy is wasted throughout the lifetime of the plant. For this reason, a great deal of effort has been put into the development of techniques that can be used to design minimum-cost networks.

The heat exchanger network design problem involves many variables and parameters. The variables are stream temperatures and exchanger heat loads. The parameters are the physical properties of the streams, the cost of exchangers, and the cost of utilities.

The major objective in network design is to minimise the total network cost. The problem involves many variables, and many possible solutions. The annual cost of the network is constrained by the inlet and outlet temperatures of the streams. The problem is thus a multi-variable or combinatorial, constrained optimisation.

Because there are many possible solutions to the network problem, at least one of the designs is best. In other words, there exists a global optimum. The challenge in network design is to find the global optimum for any given problem. In this project the best network is defined as the network that has the lowest possible total annual cost.

Because of differences in process conditions, stream properties, and economic parameters, each problem is different. These differences affect the consistency with which good network designs can be generated.

1.2 Purpose of the Investigation

The purpose of this project is to develop a technique that can be used to consistently design heat exchanger networks that are near optimal. This involves match-sequencing criteria that are based on stream properties, process conditions, and economic parameters.

1.3 Statement of the Problem

The research problem is to develop a stream matching technique that will consistently generate a near-optimal network, given:

- A number of hot process streams to be cooled from higher to lower temperatures, their heat capacity flowrates, and heat transfer coefficients;
- A number of cold process streams to be heated from lower to higher temperatures, their heat capacity flowrates, and heat transfer coefficients;
- The heat of transformation and the temperature for each process stream undergoing a phase change;
- Hot utilities and their minimum and maximum operating temperatures, heat transfer coefficients, and the cost of one unit of energy per unit time;
- Cold utilities and their minimum and maximum operating temperatures, heat transfer coefficients, and the cost of one unit of energy per unit time; and
- The cost of each exchanger; and the rate of return on capital expenditure.

In this project, a near-optimal network is one whose total cost is at least ninety percent of the target cost savings. An overview of the approach adopted to solve this problem is outlined below.

1.4 Scope of the Investigation

The steps followed to solve the problem stated above are:

1. To identify and analyse the factors that affect optimum energy recovery at a match level;
2. To develop an algorithm for network design and to convert the algorithm for match sequencing into a working computer code in Borland Pascal; and
3. To evaluate the design technique by comparing networks obtained to the best designs reported in the literature.

The solution provided in this project is limited by a number of considerations stated below.

1.5 Limitations

The number of possible heat exchanger networks increases rapidly with the number of streams. This is due to the existence of different permutations of matches for each set of stream data. A set of stream data is a specification of stream conditions and typically includes: stream type (hot or cold), supply (input) temperature, target (output) temperature, heat capacity flowrate (the product of the mass flowrate and the heat capacity), and the heat transfer coefficient. As the number of streams increases it becomes prohibitive to design all possible network structures for analysis. It thus becomes difficult to ascertain that the network chosen as the best structure is globally optimal.

Heat exchange between two streams of the same type (hot or cold) is not considered in this project. Heat engines, heat pumps, furnaces, and cooling towers are not considered in this project. Only heat exchangers are used.

Streams will not be split in the design process because the cost associated with the control equipment used to maintain the split ratios is not known.

A number of network design issues that have been raised and discussed by other investigators will not be considered in this project. The scope of the project does not allow for a thorough treatment of these topics. These topics are: retrofit network design, minimum-cost multi-pass exchangers, cost of piping materials, cost of process control equipment, network operability, flexibility or resilience, interfacing heat exchanger network design and heat exchanger design, and network controllability.

1.6 Organisation

This section presents the outline of the thesis. A brief account of the next chapters is given.

Chapter 2 is a summary of the work done by other investigators in the area of heat exchanger network synthesis. The chapter presents a brief account of different existing network design techniques. Network design issues that have arisen over the years are also highlighted.

Chapter 3 explains how in this study a hot process stream and a cold process stream are made to exchange energy optimally. This process is called Match Optimisation. Before streams that exchange energy in the network are selected, each potential pair of such streams is optimised.

Chapter 4 presents the targeting procedure used in this study, a process of estimating the minimum total cost of the network ahead of design. The general solution space for a network design problem is also defined. The solution space contains the total annual cost of any conceivable design that can be generated for the problem at hand.

Chapter 5 is the heart of the project. This chapter attempts to answer the question of how streams are to be selected, and in what order the streams are to be placed in the network, in order to minimise the network cost. It also explains how preliminary designs can be improved or evolved into near-optimal design structures. This process is called Network Optimisation. It is presented as a stream matching algorithm.

Chapter 6 describes how the network design technique developed in this project was implemented.

Chapter 7 is the presentation and discussion of the results obtained by applying the new algorithm to a carefully selected set of twenty-three literature problems. Here the new design technique is evaluated by comparing the results obtained to the best network designs reported in the literature available.

Chapter 8 gives conclusions and recommendations. This section summarises the essential features of the new network design technique. It suggests possible future improvements to the technique.

Details that support certain sections in the body of the thesis are presented in the **Appendices**.

CHAPTER 2

Review of Relevant Material

Introduction

The purpose of this chapter is to state the general network synthesis problem, highlight the different methods available to solve the problem, and state how it will be tackled in this project. The general problem statement is presented in Section 2.1. The common methods that have been used to solve the network design problem are outlined in Section 2.2. In the process of solving network design problems certain issues arise. These issues are presented in Section 2.3. Section 2.4 focuses on the objective of this project. It states why and how the project will be carried out, and how it will add to what has already been done by other investigators.

2.1. Statement of the Network Synthesis Problem

The problem for Heat Exchanger Network Synthesis has been stated clearly in the past. Although stated in slightly different forms, the meaning of the problem statement has remained essentially unchanged. A few versions of the problem statement are given below.

Masso and Rudd (1969) gave one of the early statements of the heat exchanger network synthesis problem:

> *Task Constraints.* There is a total of n_p liquid process streams n_c of which are to be heated, while the remaining $n_h = n_p - n_c$ streams are to be cooled. Associated with the k^{th} stream are its flowrate, w_k, supply temperature, T_s, target temperature, T_t, and heat capacity c_k, all in consistent units. The available auxiliary heat transfer media are saturated steam and cooling water. The steam is available at any flowrate at a pressure p_s, and is allowed to give up only its latent heat ΔH_s. Cooling water is also available at any flowrate at a temperature $T_{cu\text{-}in}$, and is allowed to undergo changes up to a maximum temperature $T_{cu\text{-}out}$.
>
> *Unsynthesized System.* The unsynthesized system has input information consisting of the stream descriptions given above, and the additional data representing further constraints to be listed below.

Existing Technology. The equipment available includes heat exchangers of the shell-and-tube type operating as counter-current, single-pass units. For the fluids and conditions prevailing, average overall heat transfer coefficients U_p, U_{hu}, and U_{cu} 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 $\Delta T_{min,p}$, $\Delta T_{min,hu}$, and $\Delta T_{min,cu}$, respectively. The equipment undergoes maintenance checks and repairs resulting in α 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 $C = C_1A^b$ where C_1 and b are constants. Cooling water costs C_w \$/lb, and steam costs C_s \$/lb. Operating and other costs are neglected. Total costs are computed on a yearly basis with fixed costs amortising linearly over a period of L years.

Synthesis Objective. The objective is to structure a system capable of performing the prescribed tasks at minimum yearly costs.

The version of the heat exchange problem given by Kobayashi et al. (1971) is:

For given specified values of temperatures and the physical properties of the streams, find the system structure of heat exchange with auxiliary heating and cooling facilities so as to minimise some objective function expressing the cost.

Rathore and Powers (1975) gave another brief statement of the heat exchanger network synthesis problem:

Consider changing the temperature of n_c cold streams and n_h hot streams from given input to specified output temperatures. Heat exchangers and utilities can be purchased to solve the problem. The goal is to find the heat exchanger network that minimises the total cost for the system.

Pehler and Liu (1981) introduced the problem of the multi-objective synthesis of heat exchanger networks. This statement is summarised below.

> There are n_h hot process streams Hi (i = 1, 2, ..., n_h) to be cooled and n_c cold process streams Cj (j = 1, 2, ..., n_c) to be heated. Associated with each stream are its supply (or input) temperature, T_s, target (or output) temperature, T_t, and heat capacity flowrate F_{cp}. There are also available n_{hu} heating utility streams and n_{cu} cooling utility streams. The synthesis problem is to create several steady-state optimum and sub-optimum networks of units so that the specified stream outlet temperatures are reached. The optimum or sub-optimum networks should achieve or nearly achieve at least the following multiple-objective criteria:
>
> 1. Approaching a practical minimum loss in thermodynamic available energy during heat exchange among hot and cold streams (that is, achieving the most efficient or nearly reversible exchange of heat among hot and cold streams);
> 2. Minimising the number of units;
> 3. Minimising the investment cost of units; and
> 4. Minimising the operating cost of utilities.

According to Liu, 1987:

> An important feature of the multi-objective synthesis problem is that some of the objective criteria may conflict with others. For instance, minimising the loss of available energy during the heat exchange process requires maximising the heat transfer area, which tends to maximise the network investment cost (Umeda et al., 1978). Also, minimising the number of units does not necessarily lead to minimising the investment cost of units, because the investment cost of units depends not only on the number of units but also on the total heat-transfer surface area of units and on how this total area is distributed among the different units (Nishida et al., 1977; Linnhoff and Flower, 1978b).

In this project the general statement presented by Rathore and Powers (1975) will be adopted. The specification of the minimum approach temperature will not be made. Furthermore, the number of units, the investment cost of units, and the operating cost of units will not necessarily be minimised. This is done because of the conflicting nature of the multiple objectives. Apart from these conditions, the approach adopted accommodates all the problem statements made above.

2.2. Techniques for Heat Exchanger Network Synthesis

Heat exchanger network synthesis is the most well developed area of Process Synthesis. Three general approaches to solving process synthesis problems have been heuristic methods, evolutionary methods, and optimisation methods. These methods are also applied to network design. Liu (1987) presented a comparison of the three methods, and according to him each of the methods has its advantages and disadvantages, as shown below.

The advantages of heuristic methods are that:

- They can be applied by hand;
- No mathematical background or computational skills are needed; and
- It is easy to generate an initial sequence for other methods.

The disadvantages of heuristic methods are that heuristics often contradict or overlap one another; and the outcome depends on which heuristics are applied first.

The advantage of evolutionary methods is that new sequences may be revealed through evolutions. The disadvantages of evolutionary methods are that:

- An initial sequence has to be generated by other methods;
- The outcome depends on which evolutionary rules are applied first;
- There is a need for quantitative performance criteria in the case of design calculations and equipment costing; and
- They are limited by the size of the problem because many sequences have to be compared.

The advantages of optimisation methods are that:

- They can be computerised; and
- It is easy to find suboptimal solutions.

The disadvantages of optimisation methods are that:

- Stream properties may be ignored;
- They depend on a cost equation; and
- They are limited by the size of the problem.

Techniques for the synthesis of a network of heat exchangers have been classified into two broad categories: sequential methods and simultaneous methods (Gundersen et al., 1991). Sequential methods typically involve the following sequence of stages: determination of utility targets, determination of the minimum number of units, determination of capital cost targets, design of a small set of promising preliminary networks, and evolution of one of the preliminary networks into a final design. On the other hand, simultaneous methods determine the minimum utility requirements, number of units, and capital costs all at once in a way that minimises the total annualised cost. The design process may involve simultaneous optimisation of the utility cost, match selection, heat exchanger area and network structure to reduce the total annual cost (Yee and Grossmann, 1990).

Jezowski (1994a) classifies network techniques into insight-driven approaches and mathematical-technique-based approaches as follows:

> Insight-driven approaches avoid application of mathematical techniques as much as possible and rely on problem understanding, thermodynamic laws and logical reasoning. The designer drives them. Mathematical approaches solve the synthesis problem as a formal optimisation task using mathematical tools. They are largely automated. A network design method may blend features from both approaches.

Network designers are faced with discrete decisions about the network structure, such as: which streams to match, in what sequence the matches should occur, how the heat loads are to be distributed among the exchangers, and whether a series or a parallel arrangement of heat exchangers is optimal.

Common design techniques that have been used in the past are discussed next. The approaches are classified into mathematical techniques and insight-based techniques following Jezowski (1994a). Some investigators use techniques that mix both approaches.

2.2.1. Mathematical Techniques

Mathematical techniques have been largely mathematical programming methods. Other mathematical techniques are tree searching algorithms and simulated annealing

2.2.1.1. Mathematical Programming

The commonly used techniques in Mathematical Programming have been Linear Programming (LP), Mixed-Integer Linear Programming (MILP), Non-Linear Programming (NLP), and Mixed-Integer Non-Linear Programming (MINLP).

i. Linear Programming

The earliest statement of the heat exchanger network synthesis problem is that which was presented by Hwa (1965). It was given as a specific problem. Briefly, his problem statement involved four hot process streams to be cooled from supply to target temperatures and three cold process streams to be heated from supply to target temperatures. A furnace and water coolers were provided to supplement the required heating and cooling. The objective was to determine the optimal configuration of the heat exchange system.

Hwa noted that linear programming as a technique to solve the problem was not suitable because the network synthesis problem is non-linear, "since the governing relationships for heat transfer and costs are non-linear." His second observation was that the problem involves a large number of variables. In order to solve the problem he applied a non-linear optimisation technique called Separable Programming. This is an extension of Linear Programming and it permits the inclusion of non-linear functions using piece-wise approximations. On the basis of "careful engineering judgement" he limited the practical heat exchanger arrangements to a small number (four) of economically attractive configurations. To permit the mathematical programming technique to determine the best configuration, Hwa found it convenient to combine the various alternative configurations into a single model. The model included all four original configurations. Elimination of the unprofitable exchangers from the model was equivalent to the determination of the optimum configuration.

In the late 1960s it was acknowledged that the size and complexity of the network synthesis problem make it practically impossible to attain the optimum arrangement of heat exchangers in the plant. This led to an attempt by Kessler and Parker (1969) to optimise the sequencing, as well as the allocation of heat in the sequence, for an arbitrary network of hot and cold streams. Kesler and Parker aimed at minimising the total cost of all exchangers in the network. They used a technique that is based on alternate use of an assignment algorithm to select new attractive bases. The assignment algorithm was basically a stream matching procedure. Each stream was fractured into heat elements and these heat elements of a stream could, "either individually or in combination with adjacent elements, exchange heat with any other single or multiple elements of another stream." This problem was solved by the linear programming method.

Kobayashi et al. (1971) formulated heat exchanger network design as an optimal design problem. They divided the optimisation problem into two parts: an optimal design problem for a given system structure, which they called the first-level problem; and an optimal structuring problem under the assumption that the first-level problem has been solved optimally, and they called this part the second-level problem. They used the Complex Method (Box, 1965) to solve the first level problem and they used linear programming to solve the second-level problem. In their design method, these workers divided the heat exchanger network into two parts: an interior heat exchange system, consisting of process exchangers only; and an exterior system consisting of auxiliary heating and cooling facilities.

In the early 1980s the calculation of minimum utility requirements was formulated as a transportation problem in linear programming (Cerda et al., 1983). The transportation problem in linear programming seeks to determine the optimum network for transporting a commodity from sources directly to destinations. In network design the commodity is heat and it is shipped from hot streams (sources) to cold streams (destinations).

A well-known variation of the transportation model is the transhipment model. The transhipment model investigates the optimum network for shipping the same commodity from sources, via intermediate nodes, to destinations. For the heat recovery problem, heat can be regarded as a commodity that is shipped from hot process and utility streams (sources) to cold process and utility streams (destinations) through temperature intervals (intermediate nodes) that account for thermodynamic constraints in the transfer of heat. Papoulias and Grossmann (1983) proposed several formulations of the transhipment model for the optimal synthesis of heat exchanger networks. They used one linear programming version of the transhipment model to predict the minimum utility cost when matches are not restricted. Another version was used to determine the minimum utility cost target when matches are restricted. Using these versions Papoulias and Grossmann (1983) solved problems involving restricted matches and multiple utilities.

ii. Mixed-Integer Linear Programming

Papoulias and Grossmann (1983) also formulated a mixed-integer version of the transhipment model. This model was used to design minimum utility cost networks in which the number of units is minimised, stream splitting can be performed, and the most preferred matches can be selected.

iii. Non-Linear Programming

The optimum design of heat exchanger networks seemed to Grossmann and Sargent (1978) to be best suited to solution by a mixed integer non-linear programming formulation. This is because the problem involves both discrete variables and continuous variables. However, at that time there was no efficient large-scale mixed-integer non-linear programming algorithm. Therefore, they considered the problem in two stages: discrete optimisation and continuous optimisation. In the stage of discrete optimisation discrete variables were optimised using an implicit enumeration algorithm coupled with heuristics. This involved determination of the sequence of matches that minimises the cost subject to maximising energy recovery. In the stage of continuous optimisation the configuration obtained in the first stage was optimised using a Non-Linear Programming algorithm. They solved thirteen standard literature problems, obtaining results that still compare favourably with those reported in other works.

Different mathematical programming techniques can be applied sequentially to solve the network synthesis problem. Floudas et al. (1986) presented a procedure for the automatic generation of optimal configurations for heat exchanger networks. According to them, the networks derived by their procedure feature the minimum investment cost subject to having the minimum utility cost and the fewest number of units. Their design procedure involves four stages:

1. The minimum utility cost and the location of the pinch points are predicted using the linear programming transhipment model (Papoulias and Grossmann, 1983). The location of the pinch points is used to divide the temperature range into sub-networks.

2. The fewest number of matches for each sub-network is predicted by the mixed-integer linear programming transhipment model (Papoulias and Grossmann, 1983). The solution to this problem provides information on the set of matches that must take place and the energy distribution.

3. A superstructure that has embedded many alternative configurations is derived. The units in the superstructure are matches that have been predicted by the mixed-integer linear programming transhipment model. The superstructure contains unknown stream connections that may define series and/or parallel arrangements, splitting and bypassing.

4. The superstructure for each sub-network is formulated as a non-linear programming problem. The investment cost of heat exchangers is minimised.. The solution to this problem provides for each subnetwork a heat exchanger configuration with the appropriate stream connections for the exchangers, as well as their flowrates and temperatures.

5. The final configuration is obtained by simply adding the configurations of each subnetwork. The automatic synthesis procedure was implemented in the computer package MAGNETS. MAGNETS stands for MAthematical Generation of heat exchanger NETwork Structures.

Using this computer package, Floudas et al. (1986) solved three network design examples to illustrate that the program can handle different design situations automatically: exchanger bypass, stream splitting, multiple pinch points, and the rigorous optimisation of the minimum temperature approach with reasonable computational effort.

Colberg and Morari (1990) also used Non-Linear Programming in their work on area and capital cost targets for heat exchanger network synthesis with constrained matches and unequal heat transfer coefficients. They formulated a pair of transhipment non-linear programs to calculate the area and capital cost targets for heat exchanger network synthesis. The networks involved:

unequal heat transfer coefficients, different capital cost laws (for different materials of construction and pressure ratings), forbidden matches, required matches with specified areas, and constraints on the number of matches. Using Non-Linear Programming, they showed that the trade-off between the area and the number of units could be evaluated before synthesis. Their approach was based on pinch principles. The first transhipment non-linear programming model was formulated for area targeting and the second model was used for capital cost targeting.

iv. Mixed-Integer Non-Linear Programming

Floudas and Ciric (1989) discussed two uncertainties associated with heat exchanger network synthesis. The first uncertainty they discussed was that "when there are several combinations of matches that satisfy the targeting criteria of minimum utility cost and fewest number of units, a minimum cost network configuration is derived only for one combination of matches that satisfies the targeting criteria." For synthesis problems of small size this uncertainty, they noted, was overcome by exhaustive enumeration of all combinations of matches that satisfy the targeting criteria. "A minimum cost network is derived for each combination, and the set of matches providing the lowest cost network configuration is chosen as optimal." They observed that for large problems this procedure could be quite cumbersome. The second uncertainty discussed by these workers was concerned with the task of network optimisation. Network optimisation can be formulated as a non-linear programming problem (Floudas et al., 1986). "Uncertainty arises because this non-linear problem is nonconvex, and thus may have several local optima." Also, the use of conventional solution techniques results in a final solution that depends upon the starting point.

To overcome the uncertainty associated with the selection of one out of many possible match combinations, Floudas and Ciric (1989) presented a decomposition methodology based upon a proposed *hyperstructure* that contains all possible network configurations and process stream matches. The hyperstructure was used to formulate a Mixed-Integer Non-Linear Programming model for both the selection of process stream matches and the derivation of a heat exchanger network configuration through simultaneous optimisation. To overcome the uncertainty associated with the network optimisation task that arises from the nonconvexities in the network optimisation problem, Floudas and Ciric (1989) proposed a "global optimum search approach that decomposes the nonconvex network optimisation problem into a set of convex subproblems that present upper and lower bounds and whose solution can lead to the network configuration with the globally minimum investment cost." They illustrated their network design strategies with six literature problems and they concluded that there can be a significant difference between the global optimum and the local optimum found by conventional solution techniques.

An approach to network design that is increasingly becoming popular is the use of simultaneous optimisation models. Yee et al. (1990) presented a general superstructure for integration, a stage-wise representation where within each stage exchanges of heat can occur between each hot and cold stream. The Mixed-Integer Non-Linear Programming model presented by Yee et al. (1990) can generate networks where utility costs, exchanger areas and selection of matches are optimised simultaneously. Their model does not rely on the assumption of fixed temperature approaches (HRAT and EMAT). Also, it does not rely on the prediction of the pinch point for partitioning into subnetworks. The model can accommodate constraints on stream matches, heat loads and stream splitting, as well as hot-to-hot and cold-to-cold matches. Yee et al. (1990) noted that the mixed-integer non-linear programming model might become more expensive if large problems are solved. Their largest example problem involved seven process streams. Its formulation involved 231 constraints and 151 continuous and 48 binary variables.

2.2.1.2. Tree Searching Algorithms

Network synthesis is essentially a search process. Given a number of possible structures, the designer searches for the best option. It is not surprising, therefore, that one of the network design techniques is the tree-searching algorithm.

Pho and Lapidus (1973) used Tree Searching Algorithms that they derived from a compact matrix representation of an acyclic exchanger network. The optimal network, which was embedded in one of the tree nodes, was located by enumerating the entire tree using a search procedure. A decision tree diagram is simply a graph rooted at one starting node such that there exists only one path from this starting node to all other nodes. Each node represents a network and the decision tree diagram therefore represents a solution space since there is a total cost associated with each feasible network. Pho and Lapidus asserted that simplifying assumptions made by the designer can restrict a search to a subset of the total search space. An example of a simplifying assumption is that each process stream can only be matched once to another process stream. As the decision tree grows large, the computation time for the direct enumeration of the entire tree can become prohibitive. Hence, the tree searching method does not eliminate the basic combinatorial difficulty of the original problem. Computational time can be reduced by making use of problem constraints such as those generated by previous experiences or physical limitations due to the specific layout of the process streams. Examples of simplifications, as stated by Pho and Lapidus (1973) are:

1. To exclude vapour to vapour matches because of their low heat transfer efficiency;
2. To avoid matching streams that can cause start-up and control problems, such as reflux and feed streams in distillation columns; and
3. To avoid matching streams that are physically too far from each other.

Further use of the tree search to design heat exchanger networks was made by Rathore and Powers (1975). They developed a forward branching scheme for the synthesis of nearly optimal networks. Forward branching is described as a depth-first tree search procedure for identifying feasible solutions. A depth-first tree search is a search that involves a complete branch traversal before the following branch is searched. In order to reduce the computer storage requirements and to synthesise only feasible networks, Rathore and Powers used an upper bound on the amount of energy integration that can occur in the system. They applied their technique to one four-stream problem.

2.2.1.3. Simulated Annealing

The subject of combinatorial optimisation consists of a set of problems that are central to the disciplines of computer science and engineering, and research in this area aims at developing efficient techniques for finding minimum or maximum values of a function of many independent variables. According to Kirkpatrick et al. (1983) there is a useful connection between statistical mechanics and multivariable or combinatorial optimisation. Statistical mechanics can be described as the behaviour of systems with many degrees of freedom in thermal equilibrium at a finite temperature. Multivariable or combinatorial optimisation can be described as finding the minimum or maximum of a given function which depends on many parameters.

Kirkpatrick et al. (1983) drew an analogy between the cooling of a fluid and the optimisation of a complex system, and proposed simulated annealing as a general method for treating a broad class of large, multivariable problems.

The principle on which the simulated annealing algorithm is based is that for a pure substance to be cooled into a perfect or nearly perfect crystal, it must be annealed by first melting and then cooling very slowly. If the substance is cooled too quickly defects are introduced into the crystal and "the resulting structure is far from the highly ordered, minimum energy, crystalline state." Since the concept of the temperature of a physical system has no obvious equivalent in the system to be optimised, Kirkpatrick et al. (1983) introduced an effective temperature for optimisation. They showed how to carry out a simulated annealing process in order to obtain better heuristic solutions to combinatorial optimisation problems.

Dolan et al. (1989) state that "the simulated annealing process consists of first 'melting' the system being optimised at a high effective temperature, then lowering the temperature by slow stages until the system 'freezes' and no further changes occur." At each temperature, the simulation is allowed to proceed long enough for the system to reach a steady state.

Dolan et al., (1989) state that simulated annealing has proved to be a practical method for solving large combinatorial optimisation problems, and that when it is applied to a problem of cost minimisation moves are accepted and rejected on the basis of a cost function. According to these workers, no heuristic arguments are needed; instead, both capital costs and operating expenses are contained in the cost function and its global minimum is sought.

Constraints can be built into the problem, and any move that violates a constraint can be rejected or penalised through the cost function. These workers assert that "several formal proofs have been given which establish that if the number of attempted moves at each temperature is infinite, simulated annealing produces, asymptotically, the global optimum solution of combinatorial optimisation problems with probability one."

These workers note that "in practice, one cannot guarantee that the solution obtained by simulated annealing in a finite amount of time is the rigorous optimum; however, the formal results suggest that a sufficiently slow annealing schedule will provide an optimal or near-optimal solution that is independent of the initial guess and the global optimum." They applied simulated annealing to network synthesis and asserted that all heuristics are discarded and a global cost function is minimised with respect to the design variables. They illustrated their technique with one literature problem.

Byfield and Ang (1994) also used Simulated Annealing to design heat exchanger networks. They used their computer program, HELIOS, to solve three case study problems.

2.2.2. Insight-based Techniques

Various techniques based on insight have been developed over the years. For convenience these techniques can be classified into three groups: Heuristic Methods, Thermodynamic-based methods, and Algorithmic-Evolutionary methods. In practice there is no clear-cut separation of the methods. Heuristics and thermodynamic arguments have been used in a single technique that is algorithmic-evolutionary in nature.

2.2.2.1. Heuristic Methods

Heuristics are rules of thumb that evolve from past experience. Two examples of network design methods that are based on heuristics are discussed briefly below.

i. Heuristic Structuring

Masso and Rudd (1969) believed that the lack of valid criteria for the selection of matches to be placed in a network led directly to the combinatorial problem of synthesising all possible structures. They proposed a design technique called Heuristic Structuring. The method involved selection of weights, which were adjusted as experience was gained from past successes and failures. Using this technique they solved three standard literature problems.

ii. A Fast Method for the Synthesis of Optimal Heat Exchanger Networks

In order to address the combinatorial difficulty in network design, Ponton and Donaldson (1974) described an alternative approach to the matching of streams that would "lead to a method of generating a synthesis tree whose branching is substantially independent of the number of streams." These workers proposed matching "the hottest hot stream with the highest cold target." The highest cold target is the cold stream that has the highest target temperature. Their network design approach also included the requirement to transfer as much heat as possible subject to temperature of approach constraints. They asserted that "the hottest/highest matching heuristic may be used alone to generate, with great ease and considerable rapidity, a near optimal exchanger network." They stated that "it may also be used, together with hottest/second highest matching to generate alternative networks for evaluation by tree searching or branch and bound." Using their method, Ponton and Donaldson solved five standard literature problems. They believed that their method was suitable for solving industrial problems of realistic size.

2.2.2.2. Thermodynamic-based Methods

A number of techniques are based on thermodynamic principles. These principles are used to discriminate against design options that do not meet certain thermodynamic criteria. This practice reduces the number of possible solutions effectively. In addition to thermodynamic arguments these techniques may use heuristics to arrive at a desired solution. Four examples of these techniques are discussed briefly below.

i. Concept of Available Energy

Umeda et al. (1978) explored thermodynamic criteria in the synthesis of heat exchanger networks. They defined availability energy and, on the basis of this definition, analysed the problem associated with energy conservation in heat exchanger network synthesis. These investigators asserted that the heat exchanger network synthesis problem could be analysed thermodynamically by considering available energy as a function of the stream temperatures.

The fundamental characteristics of the available energy provided the basis for heuristic rules that were used to synthesise heat exchanger networks. Umeda et al. (1978) used composite curves in their network design and illustrated the basic concept of a "pinch" without expressing its significance in network design. Their strategy involved:

1. Assuming a total amount of heat exchange by manipulating the composite curves;
2. Determining the thermodynamic minimum area network for the given total amount of heat exchange;
3. Improving the thermodynamic minimum area network so as to minimise the total investment

cost of the heat exchanger system without changing the given total amount of heat exchange;

4. Calculating the annual cost;
5. Repeating steps 1 to 4 so as to minimise the annual cost; and
6. Determining the optimal network.

They noted that the approach temperature is a key decision variable in determining the optimal value of the total amount of heat exchange needed to minimise the sum of the annual costs for a given heat exchange network. To deal with the combinatorial difficulty, they used a heuristic rule: "Heat exchange is made between the two streams with the nearest values of heat transfer coefficients." As an example, they discussed the problem of converting an existing crude unit pre-heat exchanger train into a new configuration.

ii. Temperature-Interval Method

In the same year that Umeda et al. (1978) presented their algorithm, Linnhoff and Flower (1978) published a thermodynamically orientated method of heat exchanger network synthesis. Linnhoff and Flower (1978) sought network optimality with respect to heat recovery rather than cost, pointing out that the overall cost is heavily dominated by the cost of energy. They called their technique the Temperature Interval (TI) method.

They noted that whatever method is used for synthesising a network, "the maximum degree of energy recovery will never be realised if the method creates at an early stage a situation which results in prohibitive constraints." They asserted that one way of avoiding such a situation is by making sure, during each step of the synthesis, that "the freedom of choice of design decisions at later steps is not prejudiced." The freedom of choice, they said, can be related to the source temperature of the next unit of heat that is to be exchanged. The higher the source temperature is, the more flexibility there is as to where the unit of heat may be placed in the network. They pointed out that the freedom of choice could be maximised, throughout the synthesis, simply by matching a hot stream section to that particular cold stream section which has the highest temperature. Although the concept of a pinch temperature surfaced in this work, its significance in network synthesis was not fully appreciated. They used the method to solve two network problems.

iii. Thermodynamic-Combinatorial Approach

Flower and Linnhoff (1980) proposed another method for network design. It was called the Thermodynamic-Combinatorial method. This approach uses thermodynamic and topological arguments to reduce the size of the combinatorial problem. According to Flower and Linnhoff (1980), if the method is used by hand, problem-individual arguments may be formulated to eliminate the combinatorial problem almost completely. By using a variety of topological and thermodynamic arguments the network design problem is kept to a manageable size.

The major arguments employed by these writers were the target temperature feasibility, the topological feasibility, and the heat load feasibility. The target temperature feasibility test was that each match bringing a stream to its target temperature must be with a process or utility stream whose supply temperature is compatible with that target temperature. The topological feasibility test was that each process or utility stream must be used in at least one match. The heat load feasibility test was that if a process or utility stream is matched once, its partner must have an equal or larger heat load. According to Flower and Linnhoff (1980), the method can be used to generate all solutions for a given problem with a prescribed degree of energy recovery, the minimum number of units, and no stream splits.

iv. Pinch Design Method

The most well known sequential method is the Pinch Design Method (Linnhoff and Hindmarsh, 1983). This method has become known as Pinch Technology. The pinch has been described as a bottleneck to energy recovery. It divides a heat exchange process into two thermodynamically separate systems, each of which is in enthalpy balance when utility targets are applied.

In summary, design of the network involves:

- Determining the pinch temperatures.
- Dividing the problem at the pinch, and designing each part separately.
- Starting the design at the pinch and moving away.
- Obeying the following constraints immediately adjacent to the pinch:

    i. Above the pinch the heat capacity flowrate of the hot stream should be less than or equal to that of the cold stream.

    ii. Below the pinch the heat capacity of the hot stream should be greater than or equal to that of the cold stream.

- Maximising exchanger loads.
- Supplying external heating only above the pinch.
- Supplying external cooling only below the pinch.
- Combining the designs above and below the pinch.
- Evolving the preliminary structure to a final network.

Pinch Technology has been successfully demonstrated in a range of industries that employ both continuous and batch operations. Linnhoff (1993) asserts that the appropriate name for the method is Pinch Analysis. The recent developments in the method are: pressure drop optimisation, multiple base case design, distillation column profiles, low temperature process design, batch process integration, water and waste water minimisation, total site integration, and emissions targeting (Linnhoff, 1993).

v. Second-law-based Optimisation

Chato and Damianides (1986) approached the problem of simultaneously optimising heat exchangers for a number of hot and cold fluids from the viewpoint of the second law of thermodynamics. Their argument was that if all inlet and outlet temperatures are established for the fluids, then the resulting entropy production rate is independent of the actual pairings of the fluids. They interpreted this situation as meaning that "optimisation with respect to size becomes essentially a maximisation of the temperature differences between the paired fluids for all the fluids considered." They used load curves (temperature/enthalpy curves) to represent process streams. Their objective was to minimise the heat transfer surface area. According to them the coldest cold fluid should be paired with the coldest hot fluid, and the hottest cold fluid should be paired with the hottest hot fluid. Ponton and Donaldson (1974) proposed the same rule. From their experience, Chato and Damianides (1986) suggested that the order of stream pairing (matching) be "established in terms of increasing outlet temperatures from the cold end towards the hot one for both hot and cold streams." The method, which involved specification of a minimum approach temperature, was simple and graphical. The technique was illustrated with two examples.

2.2.2.3. Algorithmic-Evolutionary Methods

Some of these techniques have simply been called Algorithmic-Evolutionary Method, by the authors, without further distinguishing them from the rest of the techniques in this class. Others have been given specific names that identify them. In this section those methods which have not been given individual names will be discussed next under the title *General Methods*. Techniques with unique names are discussed last.

i. General Methods

Nishida et al. (1977) proposed an algorithmic-evolutionary approach to the systematic synthesis of minimum-cost networks. Their approach used hand calculations. The method required no special mathematical background and computational skill from the user. It also provided an explicit theoretical guidance on the optimal exchange among hot and cold streams and on the optimal locations of heating and cooling utilities in the network. This was achieved by using optimisation principles first to explore analytically the necessary conditions for minimising the total heat transfer area of the network. This step involved a simple and practical algorithm called the minimum area algorithm. The next step involved a set of simple evolutionary rules to systematically modify the minimum area or nearly minimum-cost network obtained by the minimum-area algorithm. Nishida et al. (1977) concluded that the minimum area algorithm, in addition to eliminating the combinatorial difficulties which are commonly associated with other network design techniques, has an explicit provision for the use of stream splitting and for generating a cyclic network.

Linnhoff and Flower (1978) improved the preliminary networks they obtained by the Temperature Interval method in a subsequent stage called the Evolutionary Development method. In this method they presented feasibility rules which were based on generally applicable thermodynamic principles, and which allow the user to find any feasible solution starting from any other feasible structure. According to these workers, "it is not necessary to carry out an exhaustive search through a defined part of the solution space because particular network characteristics can, within certain limits, be deliberately developed and suppressed and it is possible to concentrate one's effort on the development of only those structures which appear to lead to suitable final networks." In their network design technique, Linnhoff and

Flower (1978) considered such concepts as the number of units, flexibility, stream splitting, and cyclic structures.

A network structure with the maximum energy recovery and the minimum number of units is generally considered to be optimal or near optimal. The evolutionary procedure formulated by Su and Motard (1984) was aimed at minimising the number of units in a network. The method consists of searching for all the heat load loops in the initial network structure and breaking the loops by merging heat exchangers in the same loop.

The initial network structure was developed by the Temperature Interval (TI) method proposed by Linnhoff and Flower (1978). The procedure involved two levels of loop breaking. In the first level, called primary loop breaking, the number of units in the network is reduced as much as possible without stream splitting. If the minimum number of units for the system in question is not achieved, the next level, called secondary loop breaking, is implemented. Secondary loop breaking involves stream splitting. Su and Motard (1984) used a computer to perform the loop search and loop breaking operations. Their program is called Loop Identification Algorithm (LIA). They tested their algorithm on nine problems.

Global optimality in network design is a much sought-after quality. Lee and Reklaitis (1989) presented an algorithmic-evolutionary procedure for developing improved networks with maximum energy recovery and a minimum number of units. Their goal was to achieve the global optimum network. In the work cited here they considered unpinched problems only. Their method consists of three steps. The first step is pre-analysis and it involves determination of the minimum heating and cooling requirements and the pinch point in the network, using conventional methods. The second step is network invention, and it involves synthesis of an initial feasible network with maximum energy recovery and a minimum number of units. A heuristic matching rule and a sufficient condition for the minimum number of units are used. The third step involves evolution of the initial network to the optimum network by a three-part heuristic procedure.

Lee and Reklaitis (1989) illustrated their design technique with two literature synthesis problems. They also presented results obtained for nine standard literature problems. Seven of their networks matched the best results they had seen reported in the literature at that stage. Two of their networks were better than the best corresponding designs reported. The basis for comparison was the total cost. Nonetheless, these workers pointed out that theoretical guarantees could not be provided that their technique produces globally optimum networks.

ii. Branch and Bound Method

In the period 1960 to 1970 little theoretical guidance was available for the synthesis of integrated process designs. The selection of process equipment and its integration into a flow sheet were done on the basis of experience. There was concern that more efficient designs might be excluded from the final design solutions. It was for this reason that Lee et al. (1970) proposed the branch and bound techniques of problem solving. Their intention was to guide the design engineer during the invention of integrated process designs. They suggested that "if a design engineer is confronted with an unsolvable or excessively difficult design problem he can look for, and branch to, simpler design problems which bound the original problem and for which methods of design exist." These workers believed that their approach was effective in dealing with the combinatorial nature of heat exchanger network synthesis. They applied their technique to three literature problems.

2.2.3. Combination of Mathematical and Insight-based Methods

Many other techniques have been developed for heat exchanger network synthesis. Some techniques use elements from both major categories of Mathematical Methods and Insight-based Methods. One such example is provided by Zhu et al. (1995). They proposed a heuristic method that is based on composite curves but does not rely on pinch decomposition. "The composite curves are decomposed into a number of 'blocks' (which may exceed the two blocks formed by pinch decomposition)." Matches are selected simultaneously for each block. The initial design obtained is optimised by the method of Non-Linear Programming. The technique was illustrated with three case studies.

2.3. Issues in Heat Exchanger Network Synthesis

Associated with the process of heat exchanger network synthesis are a number of issues that affect optimality of the final network design. The issues pertain to the heat exchange process and the particular technique used to solve the problem. These issues have been raised in the past, and progress has been made to address them. However, they have not been completely resolved yet. They are problem size, targeting, assumptions, specifications, optimality, match sequencing, and automation. A brief account of each of these issues is presented below.

1. Problem size

The size of a network design problem can be expressed as the number of process streams. As the number of process streams increases, the number of feasible network structures that can be generated grows rapidly. The growth rate is more than factorial. This phenomenon has been called a combinatorial difficulty, because it becomes impossible to design and evaluate all the possible networks. A network designer therefore only examines a subset of all possible designs, and that subset may or may not include the globally optimal network. A way of overcoming the combinatorial problem would be, in principle, to ensure that the subset of the solution space examined includes the global optimum and is manageable in size. None of the published techniques appears to meet this criterion.

2. Targeting

Targeting can be defined as a process whereby, assuming a specific approach temperature constraint, the minimum utility requirement, or equivalently the maximum energy recovery, and the minimum number of exchangers can be predicted (Saboo et al., 1986). The network designer then strives to achieve these targets.

Targeting by mathematical programming has been accepted as rigorous (Colberg and Morari, 1990). On the other hand, cost targeting by the Pinch Design Method has involved the assumption of equal area distribution among heat exchangers. This assumption is not likely to be realistic because the heat transfer surface area is determined by a variety of factors such as the individual stream properties and conditions that are, in general, different for each match. Ahmad (1985) states that "if the coefficients differ from each other the target is subject to some small error (usually less than 10%)." Linnhoff and Ahmad (1989) have performed cost optimisation ahead of design, a process they have called supertargeting.

Standard design targets that do not depend on any method can serve as an objective or quantitative way of evaluating the performance of different design techniques.

3. Assumptions

Because of the complexity of the network design problem it is necessary to make simplifying assumptions. These assumptions reduce the search space and also affect network optimality. If the design results are to be meaningful, the design assumptions must be realistic. Examples of common assumptions are:

- Equal values of the effective heat transfer coefficients for all exchangers;
- Unit costs for the heat exchange area have the same value or the cost correlation is the same for all exchangers;
- Use of single-pass counter-current shell-and-tube exchangers;
- No phase change of process streams;
- Temperature-independent heat-capacity flowrates of process streams; and
- Constant minimum-approach temperatures for exchanges between two process streams, and between process and utility streams.

These assumptions are unlikely to be valid in real life. Significant progress has been made over the years to eliminate or refine them. Techniques have been developed that can be used to solve synthesis problems that deviate from these simplifying assumptions (Liu, 1987).

4. Design specifications

It has been traditional to assume a value of the minimum approach temperature in network design. Such a value is chosen on the basis of experience. The main question that can be asked is why a fixed minimum approach temperature has to be specified. Hwa (1965) specified the minimum approach temperature as a computational consideration. He did this to keep a positive temperature driving force between hot and cold streams. But another question would be whether this requirement could be met without specifying a minimum approach temperature.

A typical value of the minimum approach temperature for liquid streams is 10ºC. No clear guidelines or rules have been provided for the choice of the minimum approach temperature. Investigators have reacted differently towards the use of a global minimum approach temperature. Saboo and Morari (1984) have considered the use of match-dependent minimum approach temperature if the heat transfer coefficients of the individual streams differ widely. Some investigators have felt that specification of a single, global minimum approach temperature may not be quite realistic (Trivedi et al., 1989). Attempts have also been made to optimise the minimum approach temperature (Li and Motard, 1986; Linnhoff and Ahmad, 1989).

Fraser (1989) has proposed the minimum flux as an alternative design specification. The minimum flux would replace the minimum approach temperature. The minimum approach temperature would in turn be derived for each stream from the minimum flux and the stream heat transfer coefficient. The objective of this proposal was to eliminate the multi-variable optimisation, which results when stream-dependent minimum approach temperatures are used.

In order to use stream-dependent contributions to minimum approach temperatures, Rev and Fonyo (1991) proposed the diverse pinch concept. In this approach the individual film heat transfer coefficients are taken into account at the earliest possible design stage when the film coefficients differ widely. The streams were "vertically shifted by a value proportional to the inverse of the individual film coefficients." Rev and Fonyo (1991) hoped that this approach would:

- make the driving force distribution smoother;
- provide a more realistic initial network supertargeting; and
- avoid some topological traps in the synthesis of initial heat exchanger networks.

Other workers have actually suggested that specification of the minimum approach temperature can be dropped altogether (Dolan et al., 1989; Yee et al., 1990; Sagli et al., 1990; Gundersen and Grossmann, 1990).

5. Network optimality

The ultimate objective of network design is to achieve global optimality. Because of the combinatorial difficulty, proof of global optimality has not been demonstrated. Although an effort has been made to generate globally optimal networks (Hohmann, 1971, Nishida et al., 1971; Grossmann and Sargent, 1978; Lee and Reklaitis, 1989), none of the techniques developed has been demonstrated to guarantee global optimality. Because of the nonlinear nature of the cost equation mathematical programming techniques have been hampered by the existence of local optima. On the other hand, insight-based techniques have been hampered by the existence of topology traps (Gundersen and Grossmann, 1990) when networks are evolved. According to Gundersen et al. (1991) the term topology trap in evolutionary strategies "has been used to describe the situation where the basic structure of the initial network is incompatible with the global optimum." Topology traps can be caused by the use of a wrong initial value of the minimum approach temperature, or the use of a single global value of the minimum approach temperature when the stream heat transfer coefficients differ by an order of magnitude. Local optima and topology traps make detection of the global optimum extremely difficult (Gundersen et al., 1991).

The existence of a global optimum is self-evident, yet has never been proved. The global optimum exists because the costs of the possible networks are different. That is, at least one of the possible networks is the cheapest option under the conditions stated in the stream and cost data. Given the existence of a globally optimum network for any given set of stream and cost data, design steps that lead to this optimum have been uncertain.

Proof of existence of a global optimum will be, or will lead to, a break-through in network design because it will shed some light on the nature of the globally optimum network. This means that the characteristics of a globally optimum network, once the stream and cost data are given, can be understood. Otherwise the designer is not in a position to accurately describe what is to be achieved, except that the network cost should be a minimum. The designer needs to know what the minimum total cost means in terms of the factors which influence the network cost, namely, stream properties, process conditions, exchanger cost correlations, and the cost of utilities.

6. Match sequencing

The question of match sequencing is the essence of network synthesis. It is the selection of matches to be placed in a network and the determination of the order in which these matches should occur in order to minimise the total network cost. This process may involve stream splitting, bypassing, multiple matching (two streams matched more than once), hot-to-hot and cold-to-cold matches, and integration of utilities. One or a combination of these manipulations leads to a globally optimum network. The problem is to identify the set of manipulations that achieves global optimality.

In general, placement of a match in a network affects the optimality of the successive matches, and in this manner affects the overall network optimality. The crux of the matter is to anticipate how a given match will affect successive matches. In order to quantify the consequences of individual match selections over the progress of the design Ahmad (1985) presented a concept called Remaining Problem Analysis. The essence of the analysis is that if a match is placed the consequences on the area target can be made known immediately, without completing the design. Examining the remaining problem, that is, the stream data remaining to be matched, does this. The minimum overall violation of the area target is penalised, "regardless of whatever network is constructed after the current matches are in place." The technique evaluates the area penalty resulting from both excess as well as deficient use of the available temperature driving forces. It also looks at the effect of match placement on the energy target. There is no evidence, though, that Remaining Problem Analysis guarantees global optimality.

7. Automation of network design

Within the framework of all the uncertainties and design issues mentioned above, much progress has been made in automating the heat exchanger network design process. Examples of network design programs and their major features are given below.

HEXTRAN (Challand et al., 1981) was intended to create exchanger networks that are energy-efficient, and that conform to industry construction standards. The program comprised many of the previously published network design methods (Hohmann, 1971; Boland and Linnhoff, 1978; Su, 1979), modified to produce practical designs.

Feasibility calculations included in the program take into account non-linear or irregular stream enthalpy versus temperature curves for streams that may undergo a change in phase. Also considered in the program are thermodynamic feasibility and economic feasibility. The program performs rigorous network rating calculations made with the use of an optimising simulation program. The optimising simulation program allows for an analysis of system pressure drops, heat transfer coefficients, and detailed equipment sizes.

MAGNETS (Floudas et al., 1986) was designed for the automatic generation of optimal configurations for heat exchanger networks. The design strategy that forms the basis of this program was described in section 2.2.1.1 of this chapter.

SUPERTARGET (Ahmad and Shah, 1987) applies to the targeting and synthesis of optimum energy management systems by the Pinch Design Method. It was built on test feedback from ten major companies associated with the Process Integration Research Consortium at the University of Manchester Institute of Science and Technology (UMIST) in the United Kingdom.

The interface of the program was designed to be user friendly, allowing complete flexibility and freedom to move between different tasks (such as data input, design, display, changes in streams, utilities or costs), easy orientation, graphics-driven dialogue, and interaction through the mouse and keyboard on the same problem and screen.

SPHEN (Chen et al., 1989) is a knowledge-based expert system. SPHEN stands for Synthesis of Practical Heat Exchanger Networks. The program consists of four component parts: network construction, a simulator, flowsheet, diagram construction, and a user's feedback sub-system.

According to Chen et al. (1989) the program generates network configurations which feature the minimum utility cost and the fewest number of units subject to having low sensitivity of heat recovery to uncertain factors. The uncertain factors are the fouling factor in heat exchangers, input flowrates and temperatures of the process streams, and rational distribution of pressure drops among the network branches. Integrating the expert system with a process simulator and development of a man-machine interface developed the program.

FLEXNET (Suaysompol and Wood, 1991) is based on a variable approach temperature concept. Suaysompol and Wood (1991) felt that "the minimum approach temperature difference (ΔT_{min}) constraint is too rigid and inevitably limits the *flexibility* of the designer." They proposed the Flexible Pinch Design Method (FPDM), in which the heat exchangers are not so constrained.

In this method a pinch decomposition into sub-networks above and below the pinch is used with the pinch temperatures being re-defined by energy transfer across the pinch. Matches are selected on the basis of heuristic guidelines. Optimum energy recovery and utility requirements are predicted ahead of network design by using the supertargeting procedure (Ahmad and

Linnhoff, 1989) to determine the appropriate trade-off between energy savings and capital requirements.

The targeting procedure leads to the real pinch point and the optimum value for the heat recovery approach temperature. This information is then used to determine the flexible pinch point. This is a re-defined pinch so that the fixed energy requirement determined by HRAT is maintained, but some hot and cold flexible pinch point temperatures differ from those at the pinch point.

SYNHEN (Jezowski, 1992) is a package of programs for microcomputers that are compatible with the IBM personal computer for cost-optimal heat exchanger network synthesis. SYNHEN stands for SYNthesis of Heat Exchanger Networks. The program can solve network problems that involve temperature-dependent heat capacities and multi-pass heat exchangers. Some steps of the computations have been automated using strict algorithmic methods, yet the designer is able to make some important decisions.

SYNHEN has three major stages. The first stage is pre-optimisation and its objectives are:

- To find the best value of the heat recovery approach temperature and to choose the utilities; and
- To find the best load distribution for them.

The second stage is synthesis of networks and it is based on linear programming and the loop-breaking algorithm of Su and Motard (1984). The third stage is assessment and choice of solution.

HELIOS (Byfield and Ang, 1995) was developed using a simulated annealing algorithm, a simultaneous optimisation technique. HELIOS stands for Heat Exchanger Load Integration and Optimisation Scheme. It takes into account both capital cost and energy recovery.

The third version of the program can handle stream splitting, multiple matching, different materials of construction, and different stream heat transfer coefficients. It is flexible with respect to the number of units and the size of the overall problem. It does not perform stream bypassing.

The computer packages mentioned in this section are just a few examples of the programs that have been developed to design heat exchanger networks. The choice of any of the packages depends on the nature of the results sought, and whether the program is user-friendly and affordable.

The next section illustrates why an alternative approach to network design is necessary.

2.4. Justification for the Current Project

The complexity of the heat exchanger network design problem can largely be attributed to its combinatorial nature. The existence of a large number of possible solutions, and the lack of knowledge on the characteristics of a globally optimum network make it difficult to consistently ensure network optimality.

As illustrated in the literature review above (Section 2.2), many techniques have been developed and used to solve the network synthesis problem. Yet, there is no standard way of evaluating network designs. Although cost and energy targets may guide the network design process, they are not standard performance criteria and they differ from one technique to another.

Consistent generation of optimal networks is necessary not only to ensure maximum cost savings but also to form the basis for further studies such as operability and controllability in network design. Such studies can establish the cost implications of network operability and controllability.

Since network problems are diverse, it is important that a design technique generates optimum networks all the time. According to the literature review, no technique has been shown to meet this requirement. In this project, the possibility of developing such a technique was explored.

Starting from first principles, factors that influence network optimality were identified. On the basis of the effects of these factors on optimality a stream matching procedure was developed. In order to take into account individual stream properties each match was optimised before selection. The optimum matches selected were placed sequentially in the network. The preliminary network so obtained was then evolved to a final structure. The final designs were compared to the best solutions reported in the literature, where possible. A targeting procedure was also developed to evaluate the final designs.

Summary

In the process industries significant amounts of energy are usually required to convert raw materials into finished products. Energy is provided through heat exchangers. This process involves the cost of energy and the cost of capital. It has always been desirable to minimise the cost associated with energy requirements.

Since 1965 different methods have been developed for, and applied to, the problem of heat exchanger network synthesis. According to Kessler and Parker (1969) "the size and complexity of the network synthesis problem make it practically impossible to attain the optimum arrangement of heat exchange in the plant."

The two major factors that make the network synthesis problem complex are:

- The governing relationships for heat transfer and costs are non-linear; and
- The problem involves a large number of variables (Hwa, 1965).

The consequence of the non-linear relationships for heat transfer and costs is that the feasible solution space is characterised by discontinuities and nonlinearities in a way that makes optimisation models nonconvex (Gundersen et al., 1991). This means that the cost solution obtained may be a local optimum, as opposed to a global optimum.

The occurrence of a large number of variables has led to the existence of many feasible sets of matches, sequences and configurations of stream splitting, mixing and by-passing (Gundersen et al., 1991). This situation has been referred to as the combinatorial difficulty.

Despite the complexity of the problem, a tremendous amount of work has been done in the field of heat exchanger network synthesis. In this project the network design methods have been grouped according to a classification scheme presented by Jezowski (1994a). This scheme consists of two broad categories: mathematical techniques and insight-based techniques.

The major network design obstacle that any technique has to overcome is the combinatorial difficulty. In addition to this difficulty, mathematical techniques have to overcome nonconvexities caused by the non-linear nature of the cost equation used as the objective function, while insight-based techniques have to overcome topology traps. Design issues to be considered are problem size, targeting, assumptions, design specification, network optimality, match sequencing, and automation.

From the review of literature, it was deduced that three of the factors to be kept in mind in developing a network design technique are:

- Simplifying assumptions made by the designer can restrict a search for the optimum network to a subset of the total search space (Pho and Lapidus, 1973).

- The approach temperature is a key decision variable in determining the optimal value of the total amount of heat exchange needed to minimise the sum of the annual costs for a given heat exchange network (Umeda et al., 1978).

- The overall costs are heavily dominated by the cost of energy (Linnhoff and Flower, 1978).

The literature review also revealed situations that constantly challenge the network designer. These network design situations are:

- Problem size;
- Creation of prohibitive constraints;
- Existence of multiple utilities;
- Existence of temperature-dependent heat capacities;
- Unequal heat transfer coefficients;
- Streams that undergo a change in phase; and
- Different materials of construction.

The list of design situations that arise during network design is much longer than indicated above. Given any design situation the designer tries to achieve network optimality. To achieve this objective, a number of decisions have been considered, such as cyclic networks, stream splitting, multiple matching, and stream bypassing.

This project is justifiable because, despite the fact that much progress has been made in developing and applying different techniques, there are fundamental questions that have not been answered to date. Typical design questions are whether or not streams should be split, and in what order matches should be placed in a network. Because of these uncertainties generation of networks that are consistently optimal is not guaranteed.

Generation of networks that are consistently optimal is necessary in order to ensure maximum cost savings under different design conditions, and in order to provide a basis for further studies in network design.

The approach adopted in this project was to consider factors that influence optimality at match level and at network level. Individual stream properties were integrated at match level, while energy distribution and match positions were considered at network level.

This project attempts to establish a match sequencing technique that consistently generates near-optimal networks, something which has not been convincingly demonstrated in the history of network design.

CHAPTER 3

Match Optimisation

Introduction

A match is a building block for a heat exchanger network. Since network design is a complex problem, it is worthwhile to gain some insight into the nature of a match as an entity. The insight gained can be used to best select and place matches in a network, in a manner that lowers the network cost.

The supply and target temperatures of a stream determine the maximum amount of energy it can exchange with another stream. The heat exchanger design equation and the cost equation are used to model the heat exchange process. The relation between the total annual cost and the minimum approach temperature shows the point of minimum total annual cost. This is the optimum point. The process of determining the optimum point in a match is called match optimisation.

Match optimisation is performed by allowing a hot process stream to transfer energy to a cold process stream at increasing values of the minimum approach temperature. The minimum approach temperature is increased incrementally from the smallest possible value to the largest possible value. At each interval of the minimum approach temperature the annual capital cost of the process exchanger is determined. The residual of the hot process stream is then matched with a cold utility and the residual of the cold process stream is matched with a hot utility.

Five quantities are calculated at each value of the minimum approach temperature. These quantities are: the annual cost of hot utilities, the annual cost of cold utilities, the annual cost of the hot utility exchanger, the annual cost of the cold utility exchanger, and the annual cost of the process exchanger. The sum of these cost quantities is the total annual cost.

Changing only one variable together with any dependent variable, and evaluating the total annual cost at each point performs the sensitivity of the optimum point to a variable. All the other independent variables are held constant.

Section 3.1 presents the basic assumptions made in developing and applying the network design method. This is followed by a detailed discussion of the match optimisation process in Section 3.2. The last section, 3.3, presents match classification, which simplifies automation of the match optimisation. The definitions of the different match configurations facilitate information processing during program execution.

3.1 Assumptions

In order to develop the technique to be used in this project a number of simplifying assumptions were made. This is the minimum number of assumptions often made in network design. The assumptions are listed below:

1. Counter-current shell-and-tube heat exchangers are used.
2. Flowrates as well as the inlet and outlet temperatures of the streams are specified with fixed values.
3. The enthalpy of the process streams is a linear function of temperature.

3.2 Match Optimisation

This section is divided into two major parts. The first part presents the procedure for match optimisation. The second part discusses the sensitivity of the optimum point, or factors that influence the optimum point of a match. These activities hinge upon the use of the basic heat exchanger equation, exchanger cost correlation, and the cost of utilities, all expressed as a single equation, the objective function.

3.2.1 Objective Function

The heat transfer surface area is calculated from the basic heat exchange design equation:

$$Q = AU\Delta T_{LM} \tag{3.1}$$

In Equation (3.1) Q is the energy exchanged, A is the heat transfer surface area, U is the overall heat transfer coefficient, and ΔT_{LM} is the logarithmic mean temperature difference.

The exchanger cost correlation is given as a function of the heat transfer surface area:

$$C_a = C_0 + C_1 A^b \tag{3.2}$$

where

C_a = annual capital cost of the heat exchanger

C_0 = constant cost parameter

C_1 = cost coefficient

b = exponent

The objective function is the sum of the cost of energy and the cost of capital. Let C_C be the sum of annual capital costs and C_E be the sum of annual energy costs. These quantities are defined as follows:

$$C_C = \delta_p (C_{0,p} + C_{1,p} A_p^{b_p}) + \delta_{hu} (C_{0,hu} + C_{1,hu} A_{hu}^{b_{hu}}) + \delta_{cu} (C_{0,cu} + C_{1,cu} A_{cu}^{b_{cu}}) \tag{3.3}$$

$$C_E = Q_{hu} C_{hu} + Q_{cu} C_{cu} \tag{3.4}$$

where

n_{hu} = number of hot utilities;

n_{cu} = number of cold utilities;

δ = rate of return on investment;

Q_{hu} = energy transferred from the hot utility to the cold process stream;

Q_{cu} = energy transferred from the hot process stream to the cold utility;

C_{hu} = unit cost of hot utility; and

C_{cu} = unit cost of cold utility.

The objective function, C_{tot}, is defined as :

$$C_{tot} = C_C + C_E \tag{3.5}$$

3.2.2 Procedure for Match Optimisation

Before each match is placed in a network, its optimum total annual cost is determined. The optimisation procedure is sequential, consisting of evaluation of the total annual cost over a range of values of the minimum approach temperature determined by the stream data.

Directed line segments on a temperature-enthalpy diagram represent the hot and cold process streams. A summary of the optimisation steps is given with reference to Figure 3.1.

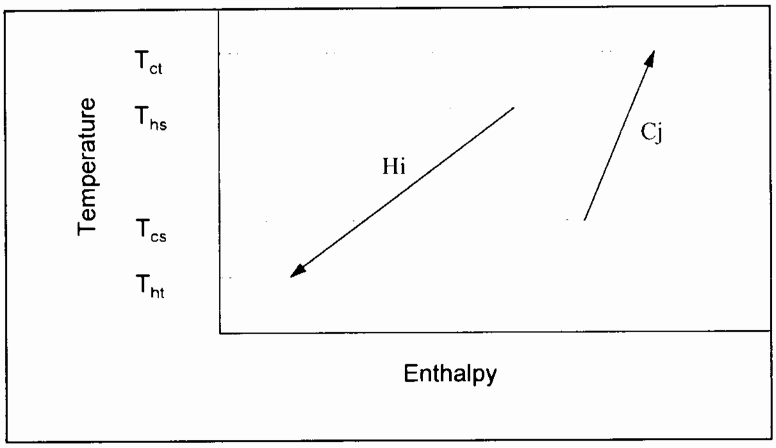

Figure 3.1: Typical match configuration

i. In case of multiple utilities, each of the process streams is fully matched with each of the utilities of the opposite type. The utility that is involved in the cheapest hot utility match is chosen as the hot utility to be used in the optimisation. This utility is called the active hot utility. The active cold utility is chosen in a similar manner.

ii. The cold process stream Cj is first positioned to the right of the hot process stream Hi (Figure 3.1).

iii. The cold process stream is shifted horizontally to the left until it touches the hot process stream without intersecting it, or until the target temperatures of the two process streams are vertically aligned. This is the initial position and is shown in Figure 3.2a. If the two lines representing the two streams touch then the annual capital cost of the exchanger cannot be calculated at this point. This is because the value of the heat transfer surface area, as predicted by the basic heat exchange design equation, is infinitely large or undefined.

iv. Next, the cold process stream is shifted to the right by an enthalpy increment. The increment is calculated by dividing the initial interval C-B by the number of data points to be taken. This results in a situation represented by Figure 3.2b. This step gives the first data point. At this point the heat exchanged, (B – C), is calculated.

The active hot utility is used to heat the residual of the cold stream to its target temperature. The active cold utility is used to cool down the residual of the hot stream to its target temperature. The total annual cost of the match is calculated by adding the annual capital costs of the process exchanger, hot utility exchanger, and the cold utility exchanger, as well as the annual costs of the hot and cold utilities. The total annual cost of the match and the minimum approach temperature are recorded.

v. The second data point is obtained by shifting the cold stream in Figure 3.2b by another enthalpy increment, as shown in Figure 3.2c. The values of the match cost and the minimum approach temperature are recorded again.

This stream shift process is repeated the pre-determined number of times. As the cold stream is shifted to the right, the temperature driving force increases. This process encourages energy transfer from the hottest end of the hot stream to the coldest end of the cold stream. At the last position, shown in Figure 3.2d, there is no energy recovery. This is a condition of maximum utility consumption.

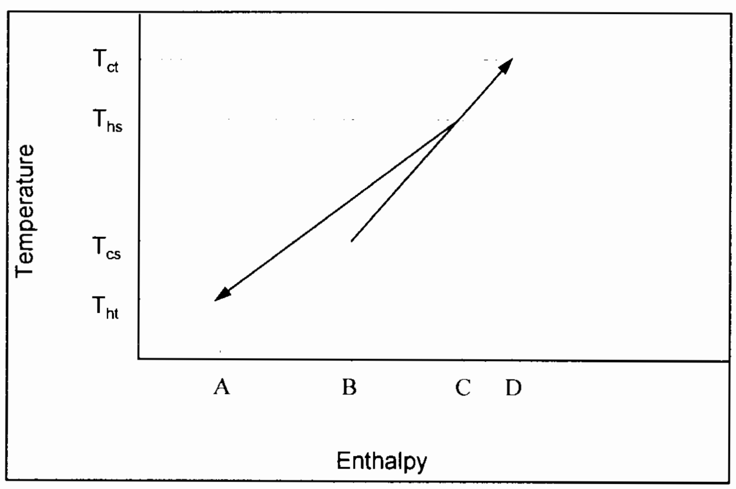

Figure 3.2a: Positions of the streams at the lowest minimum approach temperature (not drawn to scale).

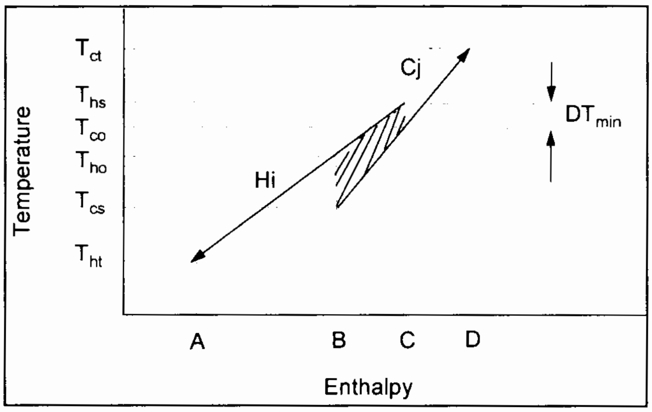

Figure 3.2b: Stream positions after the first stream shift.

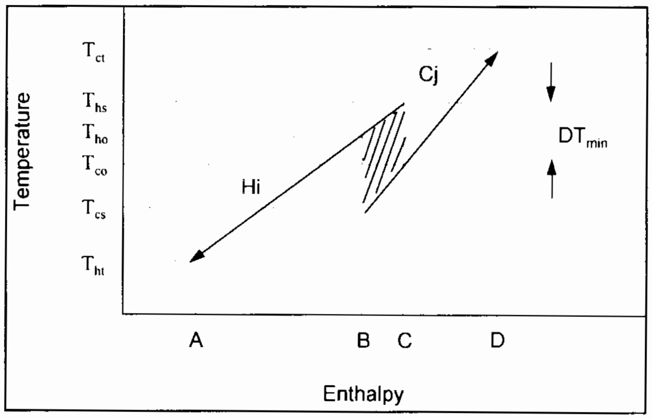

Figure 3.2c: Stream positions after the second stream shift.

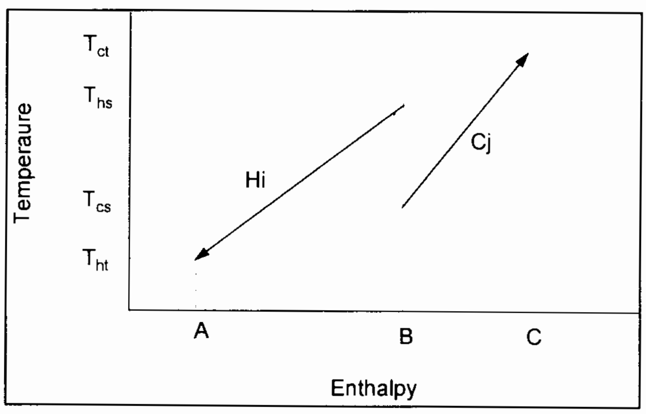

Figure 3.2d: Stream positions at the end of the stream shift process.

Quantities that can be determined during match optimisation are listed in Appendix B. To illustrate the process of match optimisation the simplest case of a heat exchanger network will be designed using the stream data presented in Table 3.1.

Example 3.1: Match optimisation.

Generation of data points

The match optimisation procedure described above was converted into a Borland Pascal computer code. The computer code was used to generate the data points.

The stream shift process described in the procedure above allows energy recovery to vary between a maximum value and a minimum value, while increasing each of the hot and cold utilities from a minimum value to a maximum value. As the minimum approach temperature is increased from the minimum value to its maximum value, the total annual cost will vary in such a way that at one point of the minimum approach temperature it attains the lowest value. The value of the minimum approach temperature at which this happens is the optimum minimum approach temperature for that match. The changes in the annual process exchanger cost, total annual hot utility cost, total annual cold utility cost, and the total annual match cost, with the minimum approach temperature are shown in Figure 3.3.

Table 3.1: Stream data and cost data (Yee et al., 1990) involving an assumed linear cost correlation for Example 3.1

Stream	T_s (K)	T_t (K)	F_{cp} (kW/K)	h (kW/(m^2 K)
H1	405	288	6	0.2
C1	293	493	5	2.0
Steam	520	520	-	2.0
Water	278	288	-	2.0

Cost data:
- Steam = 80 \$/(kW.yr)
- Water = 20 \$/(kW.yr)
- Exchanger cost (annual basis) = \$ 350 [A (m^2)]

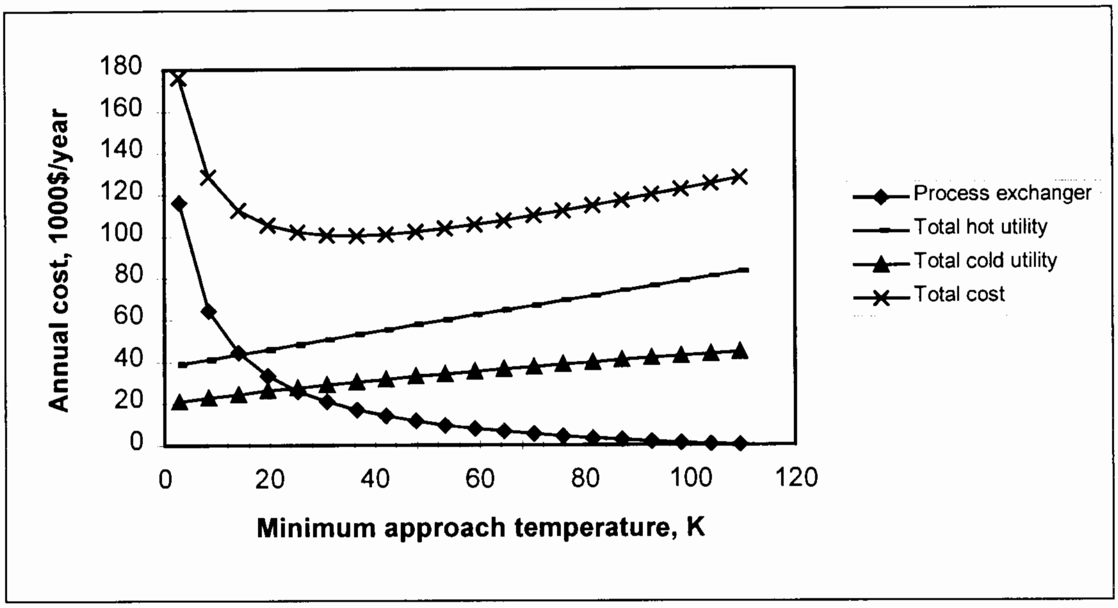

Figure 3.3: Variation of the annual capital, utility, and total annual costs with ΔT_{min}.

As shown in Figure 3.3, the total annual cost is a unimodal function of the minimum approach temperature. The diagram clearly shows the existence of an optimum. The optimum total annual cost is $100 312/year and it occurs at a minimum approach temperature of 33.7 K.

The values of the process variables at the optimum point are given in Table 3.2. For Example 3.1 the minimum hot utility requirement is 440 kW and the minimum cold utility requirement is 142 kW. Yet the optimum hot utility requirement is 608 kW and the optimum cold utility requirement is 310 kW. This example therefore shows that in order to achieve an optimum total annual cost it may be necessary to use more than the minimum amount of utilities required.

Table 3.2 shows that the sum ($C_{ce,hu}$) of the annual capital cost of the hot utility and the annual cost of the hot utility is $51 664/year, a value which is 51% of the total annual cost (C_{tot}). The sum ($C_{ce,cu}$) of the annual capital cost of the cold utility and the annual cost of the cold utility accounts for 30% of the total annual cost, and the annual capital cost of the process exchanger (C_{Ap}) accounts for 19% of the total annual cost. This indicates that the hot utilities tend to account for the highest percentage of the total annual cost. The quantities $C_{ce,hu}$ and $C_{ce,cu}$ are the total hot and total cold utility annual costs.

Table 3.2: Optimum heat exchange conditions for Example 3.1.

Process variable	Symbol	Value
Exchanger inlet temperature of the hot stream, K	T_{hi}	405.00
Exchanger outlet temperature of the hot stream, K	T_{ho}	339.75
Exchanger inlet temperature of the cold stream, K	T_{ci}	293.00
Exchanger outlet temperature of the cold stream, K	T_{co}	371.30
Hot utility requirement in the high temperature range,	$Q_{h\text{-}high}$	608.48
Hot utility requirement in the low temperature range,	$Q_{h\text{-}low}$	0.00
Cold utility requirement in the high temperature range,	$Q_{c\text{-}high}$	0.00
Cold utility requirement in the low temperature range,	$Q_{c\text{-}low}$	310.48
Energy recovered, kW	Q_r	391.52
Process exchanger area, m^2	A_p	54.02
Optimum minimum approach temperature, K	ΔT_{opt}	33.70
Process exchanger flux, kWm^{-2}	Q''_r	7.25
Percent energy recovery, %	P_r	55.77
Hot utility requirement, kW	Q_{hu}	608.48
Hot utility exchanger area, m^2	A_{hu}	8.53
Cold utility requirement, kW	Q_{cu}	310.48
Cold utility exchanger area, m^2	A_{cu}	67.24
Total hot utility annual cost, $/yr	$C_{ce,hu}$	51 664
Total cold utility annual cost, $/yr	$C_{ce,cu}$	29 743
Process exchanger annual capital cost, $/yr	C_{Ap}	18 905
Total annual cost, $/yr	C_{tot}	100
Minimum hot utility requirement, kW	$Q_{h,min}$	440.00
Minimum cold utility requirement, kW	$Q_{c,min}$	142.00

Any match involving process streams with temperature-independent heat capacities will have one optimum point because the total annual cost is a multivariable function of capital and energy, and these quantities have opposing effects on the total annual cost. The optimisation process is based on the trade-off between the cost of energy and the cost of capital. At low values of the minimum approach temperature the annual capital cost is dominant over the energy cost. At high values of the minimum approach temperature the energy cost is dominant over the annual capital cost.

For this particular problem the optimum point occurs at an intermediate position, in the range of values of the minimum approach temperature which define the minimum and maximum energy recovery. The preliminary network obtained for this simple problem is shown in Figure 3.4.

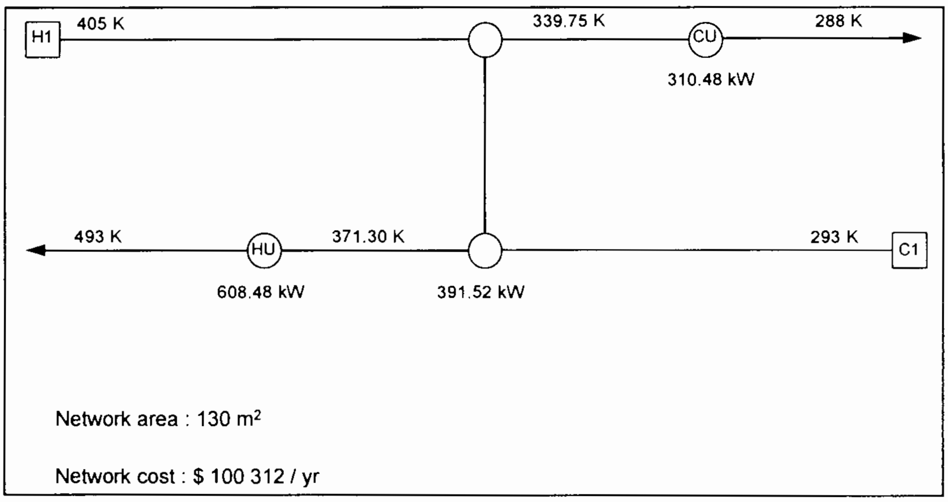

Figure 3.4: Preliminary network design for Example 3.1

In Figure 3.4 the heater is on the hotter side of the cold process stream, and the cooler is on the colder side of the hot process stream. This is an indication that when two process streams are matched, match optimality is favoured by the transfer of energy from the hottest end of the hot process stream to the coldest end of the cold process stream.

In this example it has been shown how match optimisation will be performed for all possible matches in a network. In the following section a number of factors that influence the optimum point of a match are examined in relation to Example 3.1.

3.2.3 Sensitivity of the optimum point

In this section a few hypothetical tests are performed to determine the effects of physical and economic parameters on the optimum total annual cost. Increasing a variable or parameter while keeping all the other parameters fixed at their original optimum values and observing the effect on the total annual cost does this. The tests are performed with respect to Example 3.1

The parameters tested were: the supply temperature of the hot process stream, T_{hs}; the supply temperature of the cold process stream, T_{cs}; the target temperature of the hot process stream, T_{ht}; the temperature of the hot utility stream, T_{hu}; the outlet temperature of the cold utility stream, $T_{cu\text{-}out}$; the heat capacity flowrate of the hot process stream, F_h; the heat capacity flowrate of the cold process stream, F_c; the heat transfer coefficient of the hot process stream, h_h; the heat transfer coefficient of the cold process stream, h_c; the heat transfer coefficient of the hot utility stream, h_{hu}; the heat transfer coefficient of the cold utility stream, h_{cu}; the unit cost of the hot utility, C_{hu}; the unit cost of the cold utility, C_{cu}; the cost of the process exchanger, C_{Ap}; the cost of the hot utility exchanger, C_{Ahu}; and the cost of the cold utility exchanger, C_{Acu}. Each parameter was incremented a maximum of five times by 10% of the original optimum value, subject to thermodynamic constraints. The total annual cost was evaluated at each increment. The results are summarised below. Figures 3.5a, 3.5b, and 3.5c show the variation of the optimum annual cost with changes in temperature; stream properties; and cost parameters, respectively.

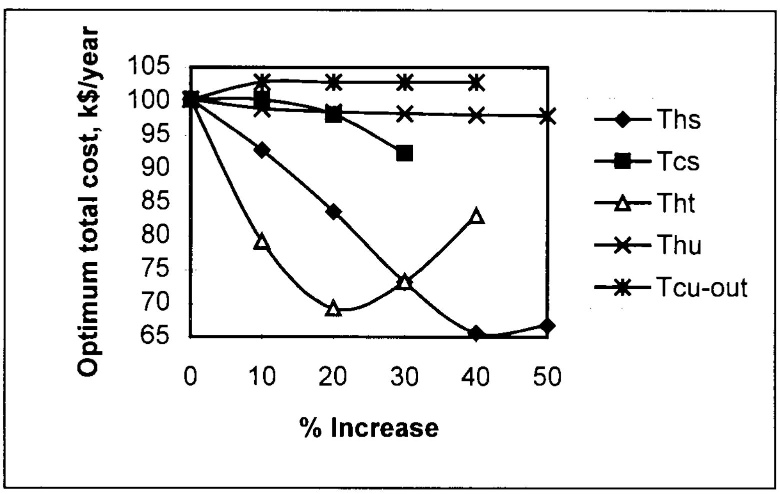

Figure 3.5a: Variation of the annual cost with the supply and target temperatures.

For Example 3.1, as shown in Figure 3.5a, the optimum total annual cost varies nonlinearly with the supply and target temperatures. An initial increase in the outlet temperature of the cold utility stream by 10% of the original value resulted in an increase in the total optimum annual cost; further increase of the outlet temperature of the cold utility stream did not change the total optimum annual cost. An increase in the supply and target temperatures of the hot process stream first resulted in a decrease, and later, an increase in the total optimum annual cost. An increase in the supply temperature of the cold process stream resulted first in a slight increase and then in a decrease of the total optimum annual cost. The initial increase of 10% in the temperature of the hot utility resulted in a decrease in the total optimum annual cost, but a further increase in this temperature made no difference.

Some of the quantities in Figure 3.5a could not be increased by as much as 50% because of thermodynamic constraints. For instance, the outlet temperature of the cold utility can only be less than the supply temperature of the hot process stream. Otherwise the cold utility will not be cold enough to cool the hot process stream. Only the supply temperatures of the hot utility stream and the hot process stream could be increased by up to 50% more than the original value. The target temperature of the cold process stream was not increased because its original value was already larger than the supply temperature of the hot process stream.

The effects observed in this section are a consequence of the assignment of temperature driving forces to heat loads. If the supply temperature of the same process stream is increased at constant heat capacity flowrate the stream load increases. If the process stream in question is to be matched against the same process stream of the opposite nature (hot or cold), then the temperature driving force is also increased. An increase in the temperature driving force tends to favour a lower heat transfer surface area, and hence, a lower annual capital cost. As the supply temperature continues to increase, the effect of the temperature driving force on the total annual cost dominates the effect of the increase in stream heat load until the total annual cost reaches a certain minimum value. After the point of minimum total annual cost has been reached the stream heat load effect becomes progressively dominant over the effect of the temperature driving force and this results in an increase in the total annual cost.

The second test performed in this section was the effect of increasing the value of a stream property of a process stream on the optimum total annual cost. The stream properties tested were the heat capacity flowrate and the heat transfer coefficient. The results are summarised in Figure 3.5b.

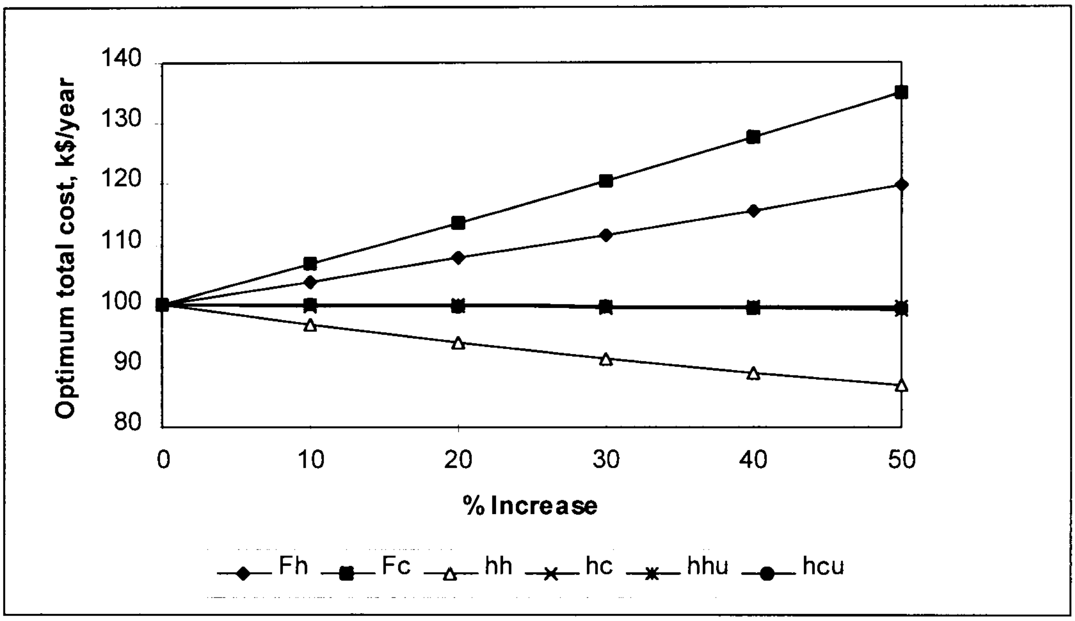

Figure 3.5b: Effects of the heat capacity flowrate and the heat transfer coefficient on the annual optimum cost for Example 3.1

The optimum total annual cost showed an almost linear increase with an increase in the heat capacity flowrate of either the hot process stream or the cold process stream. An increase in the heat capacity flowrate of a process stream at constant supply and target temperatures results in an increase in the stream heat load. If the temperature driving force is held constant such an increase leads to an increase in the optimum total annual cost, as shown in Figure 3.5b. The effect of the increase in the heat capacity flowrate is to increase the annual capital cost and/or the energy cost. Figure 3.5b also shows that the total annual optimum cost decreases almost linearly with an increase in the heat transfer coefficients. Another important observation to be made is that an increase in the value of the heat transfer coefficient of the hot process stream resulted in a larger decrease in the optimum annual cost compared to all the other streams. The value of the heat transfer coefficient of the hot process stream was smaller than any of the values of the heat transfer coefficients of the other streams, which were equal.

The relationship between the optimum annual cost and both the heat capacity flowrate and the heat transfer coefficient is linear only if the exchanger cost correlation is a linear function of the heat transfer surface area. This observation is expected, as can be seen by expressing the heat transfer surface area as a function of temperature, heat capacity flowrate, and heat transfer coefficient:

$$A = \frac{(h_h + h_c).F_h(T_{hi} - T_{ho})}{(h_h.h_c)\ln\left|\frac{(T_{hi} - T_{co})}{(T_{ho} - T_{ci})}\right|} \tag{3.6}$$

Equation (3.6) shows that the heat transfer surface area varies nonlinearly with the exchanger inlet and outlet temperatures, as well as with the heat transfer coefficients of the hot and cold streams.

The last test performed in this section involved economic factors, namely, the cost of energy and the cost of equipment. The results are illustrated in Figure 3.5c.

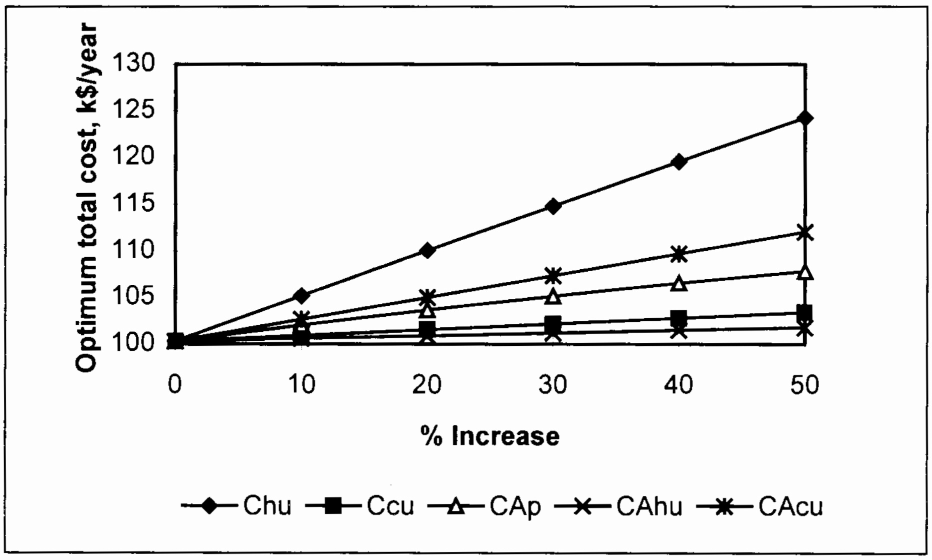

Figure 3.5c: Effects of the cost of energy and the cost of equipment on the annual optimum cost.

The total optimum annual cost increased linearly with an increase in the cost of either energy or equipment. This behaviour of the cost function is governed by Equation (3.5). For the cost data given in Table 3.1 a simpler form of Equation 3.gives the total cost C_{tot}:

$$C_{tot} = C_1(A_p + A_{hu} + A_{cu}) + Q_{hu}C_{hu} + Q_{cu}C_{cu} \tag{3.7}$$

Increasing the constant C1 in Equation (3.7) made changes in the value of the annual capital cost C_{tot} of the exchanger. Clearly, the cost is linear in C_1, C_{hu}, and C_{cu}. The cost was most sensitive to the unit cost of the hot utility, C_{hu}. This can be ascribed to the relatively high weight of the unit cost as well as the amount of the hot utility requirement. The minimum hot utility requirement was 440 kW, a value that is three times as high as the minimum cold utility requirement of 142 kW. The second most sensitive variable was the annual capital cost of the cooler. In this case the major factors are the large amount of water required for cooling and the small temperature driving force which results in a large heat transfer area requirement. The annual capital cost of the process exchanger was roughly of average sensitivity, becoming the third most sensitive of the five variables. The fourth most sensitive variable was the cold utility requirement. Even though large amounts of cooling may be required, the low unit cost of water keeps the effect of this variable relatively low. The least sensitive variable was the annual capital cost of the heater. The low cost was due to a high temperature driving force which ensured a low heat transfer area requirement and consequently, a low annual capital cost.

Even though the example discussed in this section is the simplest case of a heat exchanger network, consisting of one process exchanger, one heater, and one cooler, it has been observed that the design considerations can be quite complex. Even for this simplest case there are many possible network designs which can be generated by assigning different heat loads to the heat exchangers. Fortunately there is only one network that can be shown to be optimal for this simple case.

Since the total annual cost is a multivariable function of capital and energy costs the effect of any one variable or parameter depends on the relative weight of the particular variable or parameter. A realistic approach to stream matching would always take into consideration all variables and parameters at each step of the design process. This suggests the use of reliable and consistent evaluation criteria in stream matching involving many process matches.

In the following section different types of stream matches are examined and classified as match configurations.

3.3 Match Classification

The process of match optimisation is very tedious if done by hand. A practical way of performing match optimisation is to use computer program. The existence of different stream conditions results in different types of possible matches. Therefore, if a computer program is to be used to optimise matches, all the possible match types should be accommodated in the program. This can be done systematically by classifying matches into a finite number of identifiable configurations.

For each set of stream data the number of possible matches is finite. Each pair of a hot and a cold process stream is a match configuration, defined by the supply temperature, the target temperature, and the heat capacity flowrate of each of the two streams. Although the number of possible matches can be very high, matches can be classified into a small number of configurations that are well characterised in terms of energy recovery and utility requirements. Match configurations fall into two major categories: matches which are thermodynamically infeasible (Category A), and matches which are thermodynamically feasible (Category B).

Matches that are thermodynamically infeasible are easy to identify. In such matches the supply temperature of the cold stream is equal to or greater than the supply temperature of the hot stream. Since heat always flows down a temperature gradient, from a region of high temperature to a region of low temperature, such a match cannot result in heat transfer from the hot stream to the cold stream.

The category of interest consists of possible matches involving a hot stream whose supply temperature is greater than the supply temperature of the cold stream. The match classification scheme is illustrated in Figures 3.6a and 3.6b. The matches in this category are classified on the basis of the heat capacity flowrate into two sub-groups called classes.

The first class (B1) consists of matches in which the hot stream has a heat capacity flowrate that is higher than or equal to that of the cold stream. The second class (B2) consists of matches in which the heat capacity flowrate of the hot stream is less than that of the cold stream.

Each class is divided into two divisions. The first division consists of matches in which the heat load of the hot stream is greater than that of the cold stream (B1-1 or B2-1). The second division consists of matches in which the heat load of the hot stream is less than, or equal to, that of the cold stream (B1-2 or B2-2). Under each division there are a number of cases each of which gives insight into the heat exchange process.

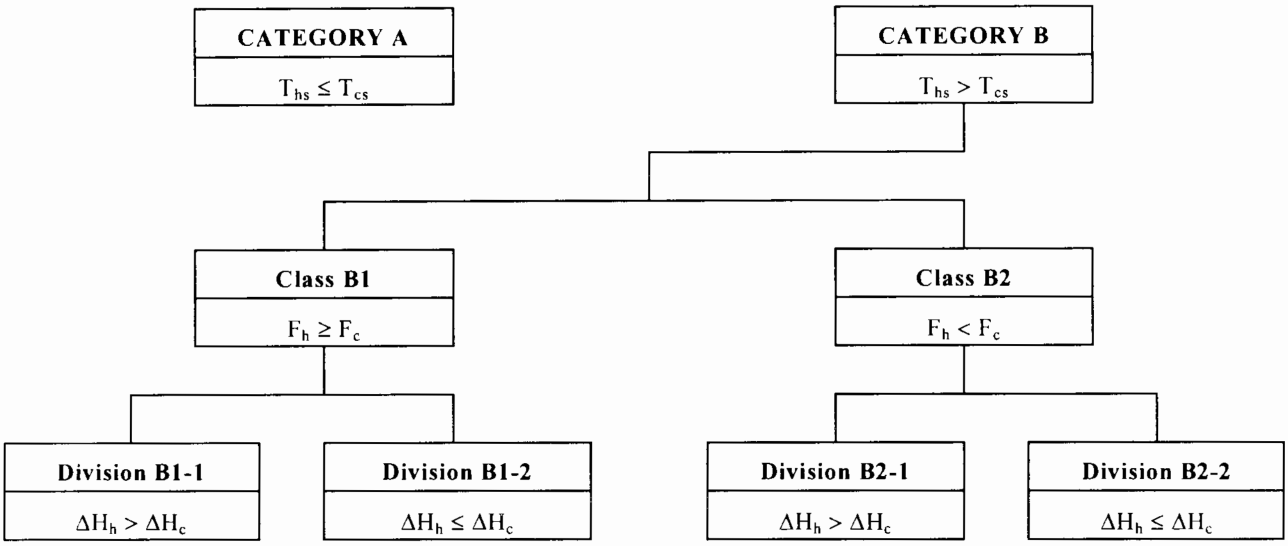

Figure 3.6a: Classification scheme for match configurations showing classes and divisions.

The different cases of conditions under each division are shown in Figure 3.6b. These cases are defined by the supply and target temperatures of the hot and cold streams. Each match configuration is completely defined by its category, class, division and case. Examples of match configurations B1-1.1 and B1-1.2 are shown in Figure 3.6c. A schematic equivalent of Figure 3.6b is shown in Appendix D. The sketches are not drawn to scale.

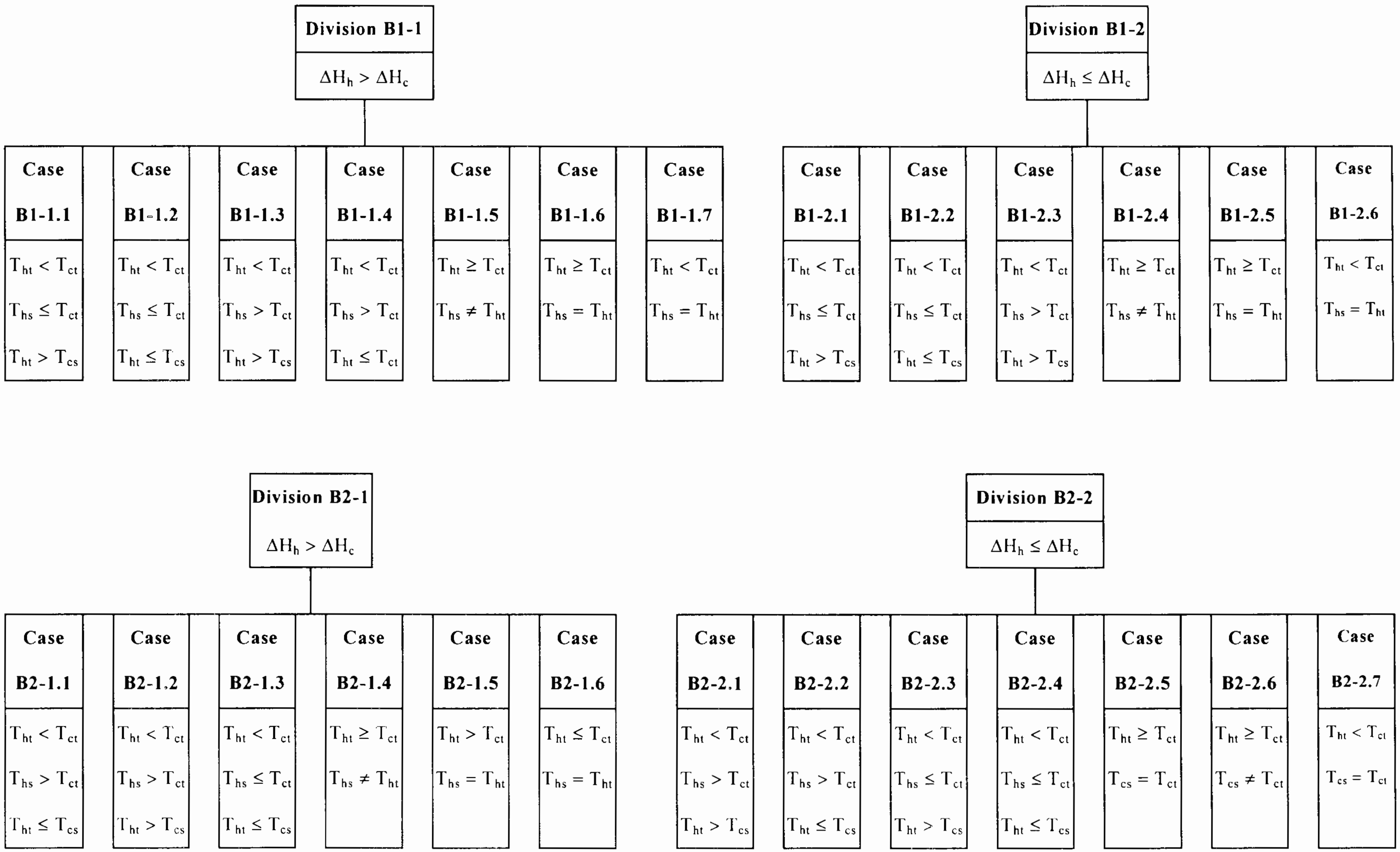

Figure 3.6b: Classification scheme for match configurations showing divisions and cases.

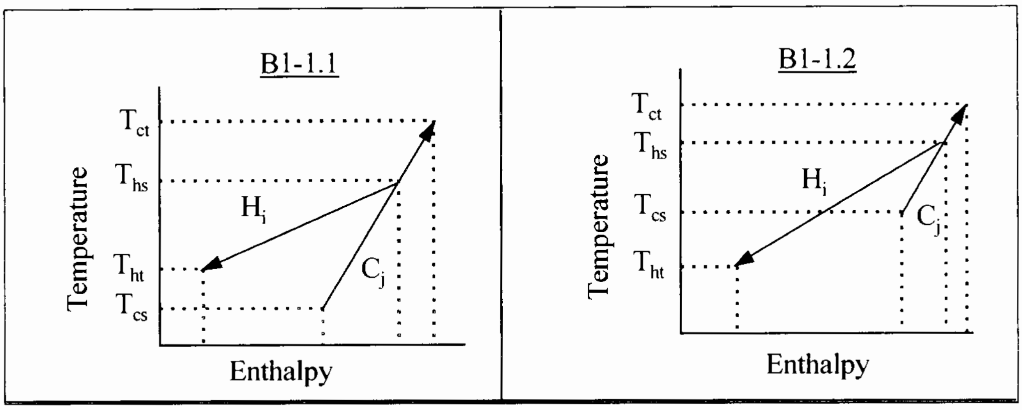

Figure 3.6c: Schematic representation of match configurations B1-1.1 and B1-1.2.

The match configurations include situations in which one stream is undergoing a phase change. For a stream undergoing a phase change it is necessary to know the energy of transformation as well as the temperature at which the phase change occurs. This information is used to determine the energy exchanged. For a stream whose heat capacity varies with temperature the stream can be divided into segments that approach a linear relationship between the heat capacity and the temperature, a linearisation process.

For a stream that involves both sensible heat and energy of transformation, the fragment that is undergoing a phase change is separated, thermally, from the stream. Each of the two fragments is treated as an individual stream.

It has been observed that each of the match configurations shows a characteristic energy profile. By energy profile is meant the variation of energy recovery and energy consumption with the minimum approach temperature. In the following section energy profiles of different match configurations are examined.

<u>Energy profiles of match configurations</u>

The data used to illustrate the variation of energy with the minimum approach temperature are given in Table 3.3 of Example 3.2.

Example 3.2: Characterisation of a match.

Table 3.3: Assumed stream and cost data used to generate the energy profile of a match.

Stream	T_s (°C)	T_t (°C)	F_{cp} (kW.(°C $^{-1}$))	h (kWm^{-2} (°C $^{-1}$))
H1	180	80	25.00	3.20
C1	20	80	16.67	3.20
HU	650	650		3.50
CU	293	308		3.50

Cost data (Yee and Grossmann, 1990)

Cost = 8600 + 670[A (m^2)]$^{0.83}$ for all exchangers

Hot utility = 80 $/(kW.yr)

Cold utility = 20 $/(kW.yr)

Figure 3.7a shows the match configuration defined by the stream data in Table 3.3.

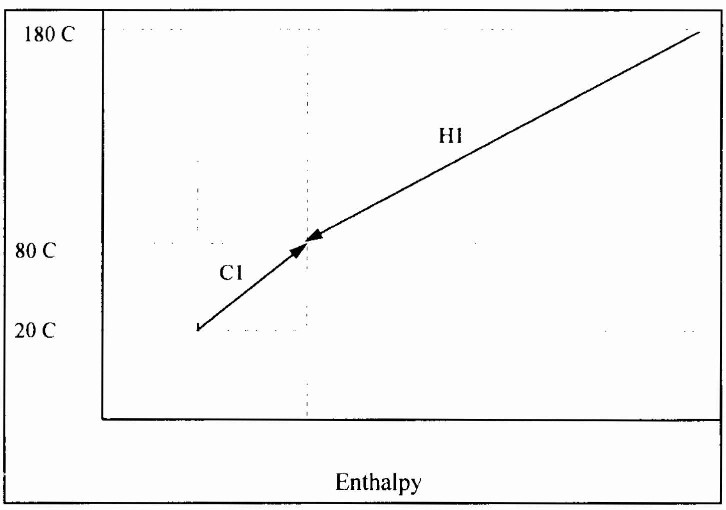

Figure 3.7a: Sketch (not drawn to scale) of a match configuration defined by the data shown in Table 3.3.

When the cold process stream C1 in Figure 3.7a is moved to the right by small increments of the minimum approach temperature the energy requirements change as shown in Figure 3.7b.

For each data point the value of energy has been scaled as a percentage of the highest value of the energy recovered. As the minimum approach temperature increases from 2 °C to about 40 °C, the energy recovery increases linearly from a minimum value to a maximum value. In the same region of the minimum approach temperature the hot utility requirement decreases linearly to a minimum level, while the cold utility requirement also decreases linearly to a minimum value. For convenience, this region of the minimum approach temperature in which energy recovery increases is called the ***pre-recovery region***.

When the minimum approach temperature is increased from 40 °C to about 100 °C the energy recovery stays constant at its maximum value. In this region the hot utility requirement remains constant at its minimum level, while the cold utility requirement also remains constant at its minimum level. This is a region of maximum energy recovery and the energy exchanged is equal to the complete heat load of one of the two process streams matched. This region is called the ***recovery region*** and is defined as a region of the minimum approach temperature in which one process stream transfers or receives its entire heat load to or from the other process stream. This region corresponds to what has been called the threshold case, a situation in which a utility requirement remains constant despite a change in the minimum approach temperature. In this region only one of two utilities is required because one of the process streams transfers (or receives) all of its heat load to (or from) the other process stream. For the case in which the hot process stream and the cold process stream have equal heat loads this region is a point rather than a range of points. It is a region of minimum utility requirement for a given match. The percentage energy recovery is 100% in this region.

As the minimum approach temperature increases beyond 100 °C the energy recovery decreases from the maximum value to its minimum value. In the same region, the hot utility requirement increases from its minimum value to a higher value, while the cold utility requirement also increases from its minimum value to a higher value. This region, in which energy recovery decreases with an increase in the minimum approach temperature, is called the ***post-recovery region***.

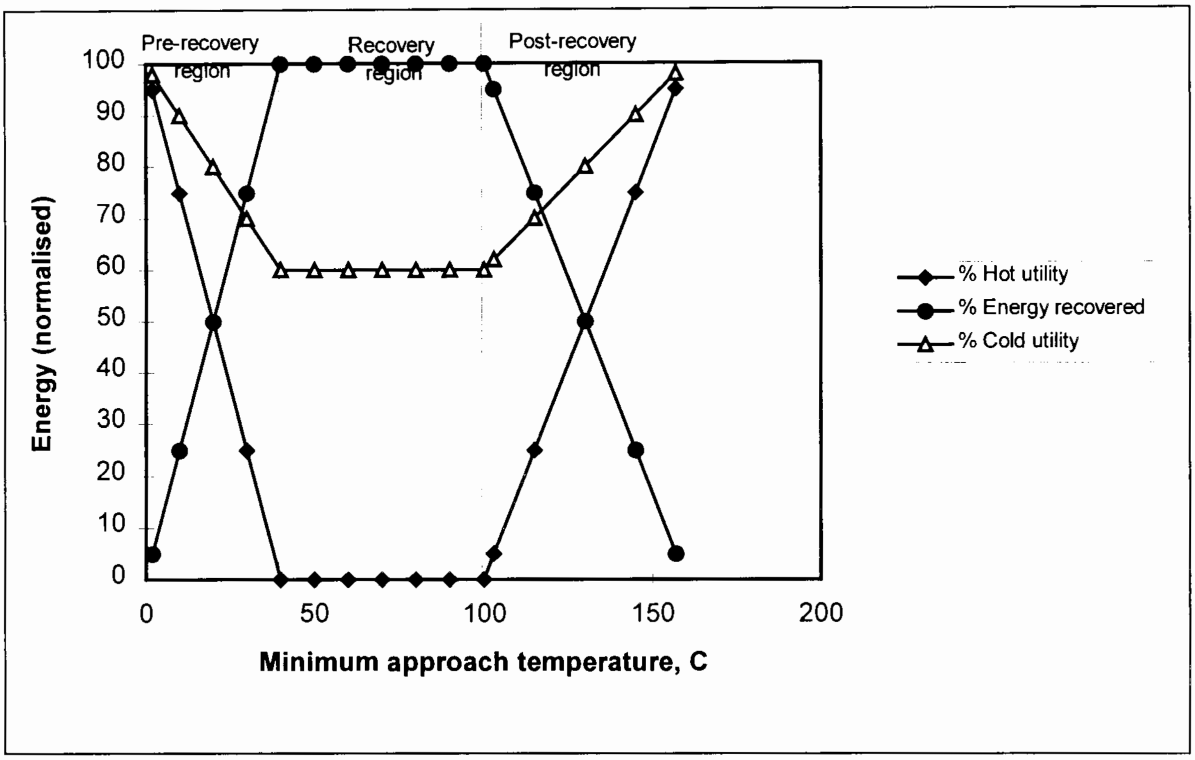

Figure 3.7b: Characterisation of a match on the basis of energy consumption.

A match may have all three energy recovery regions, may lack the pre-recovery region and have only the recovery and post-recovery regions, or may have only the post-recovery region.

Monitoring energy recovery as the minimum approach temperature is increased from the lowest non-negative value to the highest value at which energy exchange occurs generates these regions. For this reason, as well as the fact that streams are represented as straight lines inclined to the right, the combinations of the recovery regions mentioned above are the only ones possible.

A significant observation is that for any match configuration there is always a minimum total annual cost. The total annual cost of a match, as a function of the minimum approach temperature, is monotonic. It may not have a turning point, but it will always show a minimum value. The significance of this observation is that any match can be implemented at a minimum total annual cost. Twenty-six possible match configurations were identified in this project, as defined in the match classification scheme. The classification scheme is convenient for the automation of the design algorithm. Examples of match configurations, together with their cost profiles, are presented in the next example.

Example 3.3: Cost profiles of matches.

The different match configurations listed in Table 3.4a below have been compiled by modifying stream and cost data originally presented by Yee and Grossmann (1990). The cost data used in this example are given in Table 3.4b. In this example, matches involving phase changes have not been included.

The cost curves obtained by plotting the total annual cost, cost of the process exchanger, total annual cost of hot utilities, and total annual cost of cold utilities, are shown in Figure 3.8. As can be seen in Figure 3.8, the cost curve can take different shapes, depending on the stream properties, process conditions, and economics. No matter what the conditions are, the match has an optimum point.

If the conditions change, a new optimum point is created. For instance, the only difference between match configurations B1-2.3 and B1-2.4 in Table 3.4a is the target temperature, and hence the heat load of the cold process stream. The cost curves for these two cases are different, as shown in Figure 3.8. The optimum minimum approach temperature for case B1-2.3 is 132 K and the corresponding annual cost is \$ 22 928/year. On the other hand, the optimum minimum approach temperature for case B1-2.4 is also 132 K, but the annual cost is \$ 13 924/year.

The significance of match optimisation as investigated in this chapter is that the annual cost of a match is determined by a number of factors, namely, process conditions (temperatures and heat capacity flowrates), stream properties (heat transfer coefficients), and cost parameters (cost of exchangers and energy). These different factors also influence the network annual cost, and must therefore be considered during match selection. It is convenient to compare matches at their optimum conditions before placement in a network.

Table 3.4a: Match configurations for Example 3.3

Case	F_h (kW/K)	F_c (kW/K)	ΔH_h (kW)	ΔH_c (kW)	T_{ht} (K)	T_{ct} (K)	T_{hs} (K)	T_{cs} (K)	h_h (kW/m^2.K)	h_c (kW/m^2.K)
B1-1.1	6.161	1.690	1078.17	427.57	353	566	528	566	3.20	3.20
B1-1.2	6.161	1.690	1078.17	348.14	353	566	528	360	3.20	3.20
B1-1.3	6.161	1.690	1398.55	427.57	353	566	580	566	3.20	3.20
B1-1.4	6.161	1.690	1398.55	348.14	353	566	580	566	3.20	3.20
B1-1.5	6.161	1.690	1078.17	45.54	353	340	528	313	3.20	3.20
B1-2.1	2.931	1.690	118.17	427.57	519	566	560	313	0.05	3.20
B1-2.2	2.931	1.690	175.85	427.57	300	566	360	313	0.05	3.20
B1-2.3	2.931	1.690	296.03	427.57	519	566	620	313	0.05	3.20
B1-2.4	2.931	1.690	296.03	316.03	519	500	620	313	0.05	3.20
B2-1.1	6.161	7.179	1078.17	165.12	353	520	528	497	3.20	0.65
B2-1.2	6.161	7.627	1078.17	945.75	353	450	528	326	3.20	0.33
B2-1.3	6.161	7.179	1078.17	832.76	353	613	528	497	3.20	0.65
B2-1.4	6.161	7.627	850.22	259.32	390	360	528	326	3.20	2.5
B2-2.1	2.931	7.179	296.03	832.76	519	613	620	497	0.05	0.65
B2-2.2	2.931	7.179	296.03	667.65	519	613	620	520	0.05	0.65
B2-2.3	30	40	2010	2400	333	413	400	413	1.6	1.6
B2-2.4	2.931	7.179	296.03	667.65	519	613	620	520	0.05	0.65
B2-2.5	2.931	7.179	113.24	454.38	580	560	620	497	0.05	0.65

Table 3.4b: Utilities and cost data for Example 3.3

Case	$T_{hu\text{-}in}$ (K)	$T_{hu\text{-}out}$ (K)	$T_{cu\text{-}in}$ (K)	$T_{cu\text{-}out}$ (K)	h_{hu} (kW/m^2.K)	h_{cu} (kW/m^2.K)	C_{hu} ($/kW.hr)	C_{cu} ($/kW.hr)
B2-1.2 & B2-2.3	680	680	293	313	4.8	1.6	80	20
	Exchanger cost: $1000A^{0.6}$ for all exchangers except heaters $1200A^{0.6}$ for heaters							
All others	680	680	288	293	2.5	2.5	80	15
	Exchanger cost: $5500 + 150A^{0.6}$ for all exchangers							

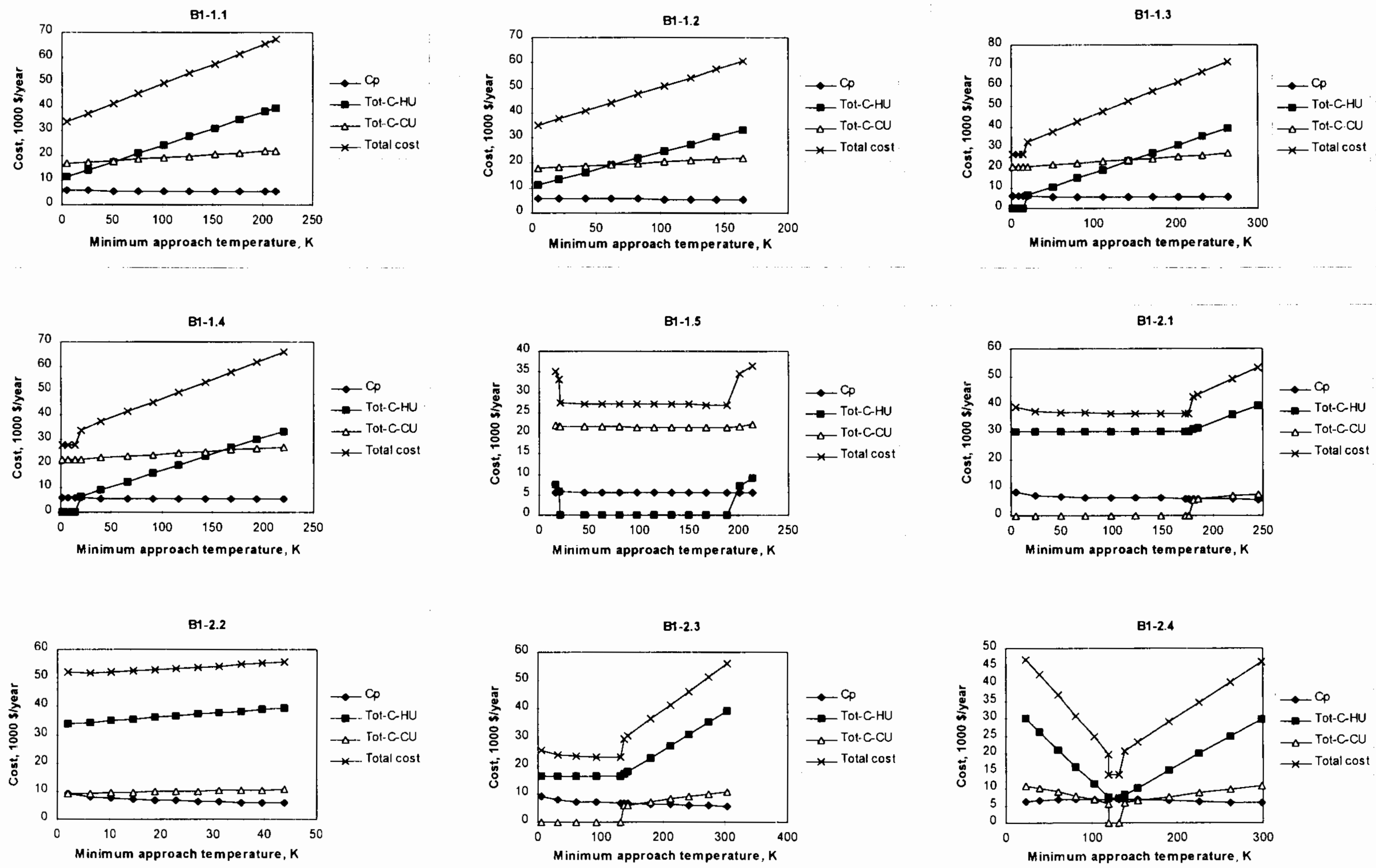

Figure 3.8: Cost curves for Example 3.3

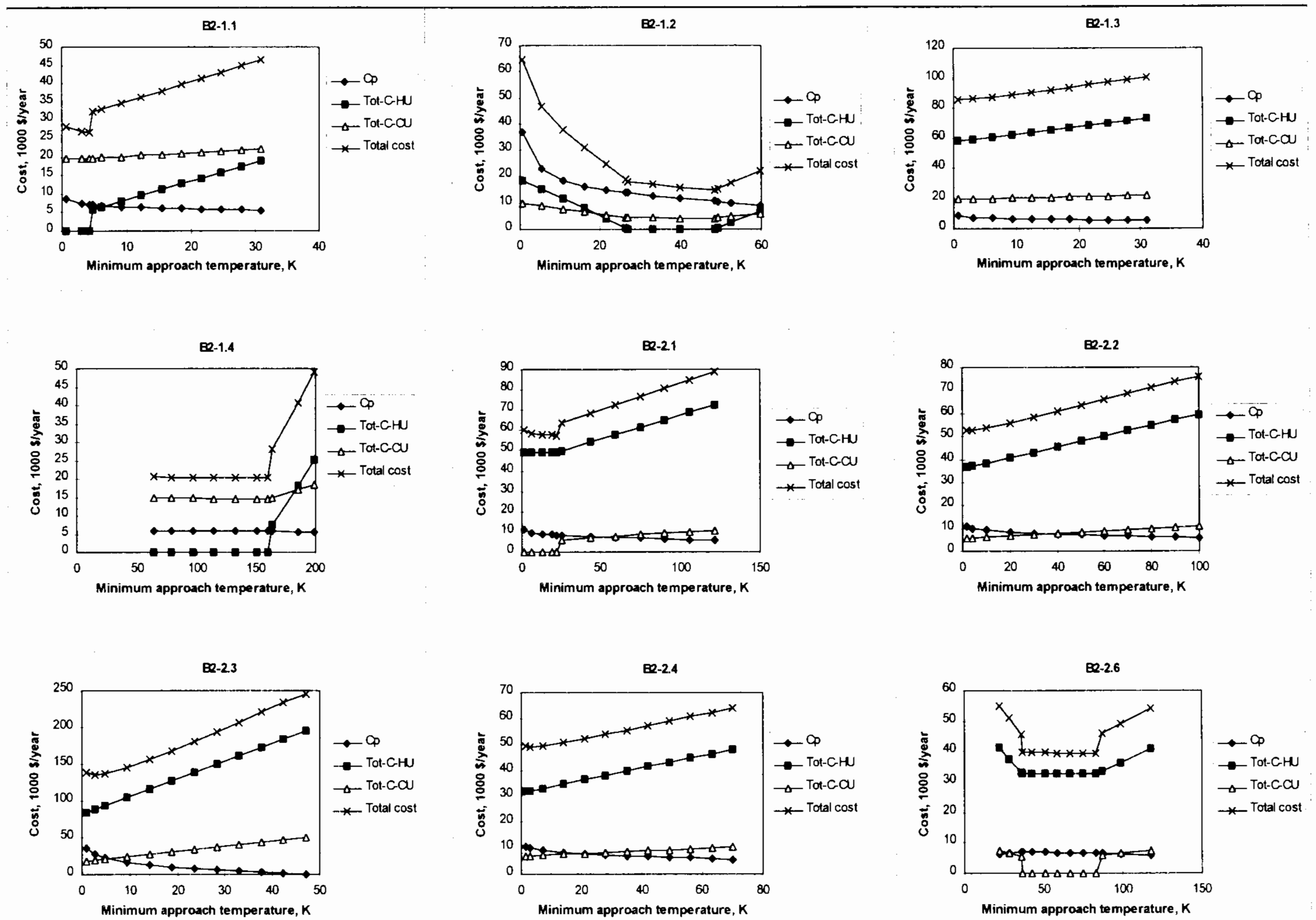

Figure 3.8: Cost curves for Example 3.3 (continued).

Summary

Because of the complexity of the network design problem, it is necessary to make simplifying assumptions. Three assumptions were stated at the beginning of this chapter:

1. Heat exchangers used are of the counter-current shell-and-tube type.
2. The values specified for flowrates as well as the inlet and outlet temperatures are fixed.
3. The enthalpy of the process streams is a linear function of temperature.

The focus of this chapter is the match. The match is a building block for networks. Because networks are complex, it is worthwhile to understand the nature of a match. The nature of a match is expressed in terms of energy recovery or the total annual cost.

Energy recovery varies with the minimum approach temperature. In a pre-recovery region energy recovery increases with the minimum approach temperature. In a recovery region energy recovery stays constant as the minimum approach temperature increases. Lastly, in a post-recovery region energy recovery decreases as the minimum approach temperature increases.

The supply temperatures, target temperatures, and heat capacity flowrates of a hot stream and a cold stream define a match configuration. Twenty-six match configurations were identified and classified. The significance of these match configurations is that different types of matches can be optimised by a computer program. Match optimisation is too tedious if done by hand. Matches are optimised because they are compared at their optimum conditions during match selection.

A match is optimised by varying the minimum approach temperature and monitoring the total annual cost. Although the match cost is a function of many variables, match optimisation with respect to the minimum approach temperature transforms it into a function of a single variable. This transformation makes it easy to identify the minimum approach temperature at which the total annual cost is lowest. The point at which the annual cost reaches its lowest value is called the optimum point. The optimum point is determined by a numerical method, as opposed to an analytical method.

For any match there is an optimum point. Heat transfer from the hottest end of the hot stream to the coldest end of the cold stream favours the optimum point.

There are parameters and variables that influence match optimality. The parameters that influence match optimality are the supply temperature, target temperature, cost of exchangers, cost of utilities, heat capacity flowrate, and the heat transfer coefficient. The variables that affect match optimality are the exchanger inlet and outlet temperatures of the streams matched, or the match heat load.

In this chapter it was observed that it might be necessary to use more than the minimum utility requirements to achieve the optimum total annual cost for a single match.

The total annual cost of a match consists of three terms: the total annual cost of hot utilities, the total annual cost of cold utilities, and the cost of process exchangers. On the basis of one unit of energy exchanged, the total annual cost of hot utilities tends to account for the largest percentage of the total annual cost. On the same basis the total annual cost of cold utilities tends to be less than the total annual cost of hot utilities but higher than the annual cost of process exchangers.

CHAPTER 4

Targeting

Introduction

In network design it has become common practice to determine the minimum utility requirements and the minimum capital investment ahead of design. This process is known as targeting. Although targeting by the non-linear programming method is accepted as rigorous (Gundersen et al., 1991), targeting by the insight-based techniques involves an uncertainty associated with area distribution among the units when the cost of exchangers is a non-linear function of the heat transfer surface area. In order to establish the capital cost targets the designer has to know the heat transfer surface area of the units. A reasonable assumption that has been made in the past, when using an insight-based technique such as the Pinch Design Method, is that the total heat transfer surface area is distributed equally among the units.

The assumption of equal area distribution is unlikely to be valid; it is an exception rather than a norm. This is because streams generally have different properties and the heat transfer surface area is therefore match-dependent, and it generally differs from match to match.

In this project a new approach to targeting is adopted. There is no specification of the minimum approach temperature. The targeting procedure is based on the concepts of a *Selection Matrix* and a *match unit cost*. The Selection Matrix is a two-dimensional array of all possible matches associated with a given set of stream and cost data. The match unit cost is the cost of exchanging one unit of energy per unit time between two streams.

The targeting procedure is developed and described in different sections. In Section 4.1 the Selection Matrix is described. New terms to be used in this project are defined in Section 4.2. Network cost limits are described in Section 4.3. The use of the targeting method in network evaluation is discussed in Section 4.4. The targeting procedure is illustrated with an example and the chapter is concluded with a summary.

4.1. The Selection Matrix

A generalised Selection Matrix is shown as Table 4.1. Hot streams identify the rows of matches in the matrix while cold streams identify the columns of matches in the matrix. Each cell in the matrix, which involves a (hot or cold) process stream and either a process or a utility stream of the opposite nature (cold or hot), represents a probable match.

Table 4.1 shows probable matches when there are n_h hot process streams, n_c cold process streams, n_{hu} hot utility streams, and n_{cu} cold utility streams. The section of the Selection Matrix that contains process matches only is called the process sub-matrix; the section that contains cold utility matches only is called the cold utility sub-matrix; and the section that contains hot utility matches only is called the hot utility sub-matrix.

Table 4.1: A generalised Selection Matrix.

	C1	**C2**	...	**Cn$_c$**	**CU1**	...	**CUn$_{cu}$**
H1	[H1,C1]	[H1,C2]		[H1,Cn$_c$]	[H1,CU1]	...	[H1,CUn$_{cu}$
H2	[H2,C1]	[H2,C2]	...	[H2,Cn$_c$]	[H2,CU1]	...	[H2,CUn$_{cu}$
...	...	...	...	...	...	...	...
Hn$_h$	[Hn$_h$,C1]	[Hn$_h$,C2]	...	[Hn$_h$, Cn$_c$]	[Hn$_h$, CU1]	...	[Hn$_h$,CUn$_{cu}$
HU1	[HU1,C1]	[HU1,C2]	...	[HU1,Cn]			
...	...	...	...	...			
HUn$_{hu}$	[HUn$_{hu}$,C1]	[HUn$_{hu}$,C2]	...	[HUn$_{hu}$,Cn$_c$]			

New terms that are used in this project are defined in the next section.

4.2. Definition of New Terms

The targeting procedure to be described in the next section is new. Therefore it is necessary to define new terms that will make the procedure understandable. These terms are defined next.

1. <u>Match unit cost</u>, c_{ij}

The match unit cost, c_{ij}, is defined as the cost of transferring one unit of energy per unit time from hot stream i to cold stream j. Mathematically, it can be defined as:

$$c_{ij} = \frac{\delta[C_0 + C_1(\frac{Q}{U.\Delta T_{LM}})^b] + Q.C_u}{Q} \tag{4.1}$$

The quantity Q is the energy exchanged and C_u is the unit cost of the utility that transfers or receives heat. This means that for a utility match C_u is nonzero, and for a process match C_u is zero. The subscript i stands for the hot process stream and the subscript j stands for the cold process stream.

The major attractive feature of the match unit cost is that for any given match it takes into consideration all the important variables and parameters affecting the particular match. It reflects the cumulative effect of these quantities.

The match unit cost will be used to define cost limits and to make decisions in match sequencing. Before any match is selected for placement in the network, all feasible and allowable matches in the process sub-matrix are optimised. Then, each cold process stream in the hot utility sub-matrix is matched with each hot utility, where possible, and each hot process stream in the cold utility sub-matrix is matched with each cold utility, if this is feasible. For each match in the Selection Matrix the match unit cost is determined. One of the matches in the process sub-matrix will have the smallest value of the match unit cost. Let this value be called $c_{p,min}$.

For each process stream, there will be a utility that is cheapest, as reflected by the value of the match unit cost. This utility will be called the active utility and will be used in match optimisation involving the particular process stream. In the hot utility sub-matrix one of the matches will have the smallest value of the match unit cost, denoted by $c_{hu,min}$. The subscript *hu* stands for the hot utility. Similarly, there will be a smallest match unit cost in the cold utility sub-matrix, denoted by $c_{cu,min}$. The subscript *cu* stands for the cold utility.

2. Absolute hot utility requirement, $Q_{h,abs}$

A cold process stream may have a target temperature that is higher than all the supply temperatures of the hot process streams in the network. When this is the case, a hot utility must be supplied to meet the energy requirements of the hottest segment of the cold process stream. Such an energy requirement is called the absolute hot utility requirement.

Let

$T_{his,max}$	=	Supply temperature of hot stream i with the highest supply temperature;
$T_{cjt,high}$	=	Target temperature of cold stream j whose target temperature is higher than the highest hot stream supply temperature;
$T_{cjs,high}$	=	Supply temperature of cold stream j which has a target temperature higher than the highest hot stream supply temperature;
T_{cjs}	=	Supply temperature of cold stream j;
F_{cj}	=	Heat capacity flowrate of cold stream j;
K_c	=	1 if $T_{cs} < T_{his,max} < T_{ct}$
	=	0 if $T_{his,max} \geq T_{ct}$
L_c	=	1 if $T_{his,max} \leq T_{cs}$
	=	0 if $T_{his,max} > T_{cs}$

The absolute hot utility requirement $Q_{h,abs}$ is defined as follows:

$$Q_{h,abs} = \sum_{j=1}^{n_c} K_c F_{cj} (T_{cjt,high} - T_{his,\max}) + \sum_{j=1}^{n_c} L_c F_{ck} (T_{cjt,high} - T_{cjs,high}) \tag{4.2}$$

The temperatures defined above are illustrated in Figure 4.1.

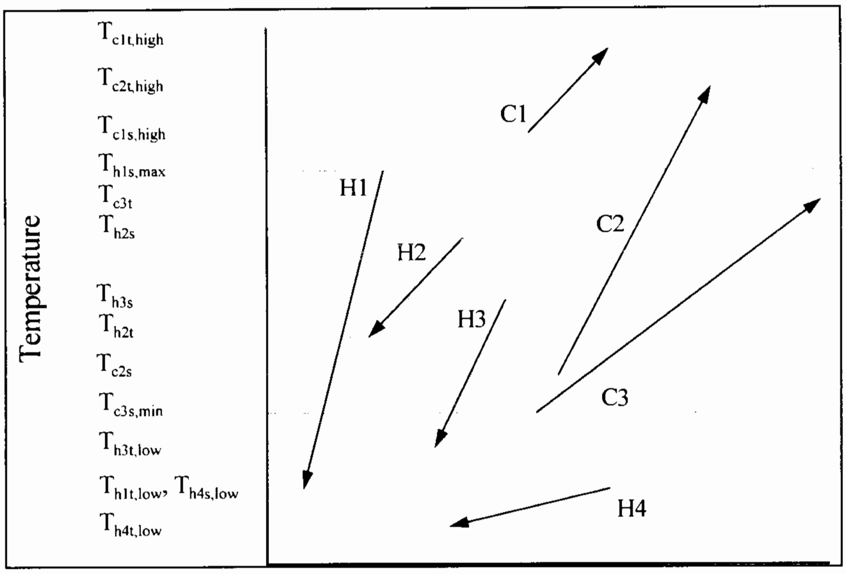

Figure 4.1: Stream temperatures used in the targeting process

3. <u>Absolute cold utility requirement</u>, $Q_{c,abs}$

When the target temperature of a hot process stream is lower than all the supply temperatures of the cold process streams it is necessary to supply a cold utility. There is an absolute cold utility requirement, otherwise the complete energy requirement of the cold process stream cannot be met.

Let

$T_{hit,low}$ = Target temperature of hot stream i whose target temperature is lower than the lowest cold stream supply temperature;

$T_{cjs,min}$ = Supply temperature of the cold stream j with the lowest supply temperature;

$T_{his,low}$ = Supply temperature of hot stream i whose supply temperature is smaller than or equal the lowest cold stream supply temperature;

F_{hi} = Heat capacity flowrate of hot stream i;

$K_h \quad = \quad 1$ if $T_{ht} < T_{cjs,min} < T_{hs}$

$K_h \quad = \quad 0$ if $T_{ht} \geq T_{cjs,min}$

$L_h \quad = \quad 1$ if $T_{hs} < T_{cjs,min}$

$L_h \quad = \quad 0$ if $T_{hs} \geq T_{cjs,min}$

The absolute cold utility requirement $Q_{c,abs}$ is defined as follows:

$$Q_{c,abs} = \sum_{i=1}^{n_h} K_h F_{hi} (T_{cjs,min} - T_{hit,low}) + \sum_{i=1}^{n_h} L_h F_{hi} (T_{his,low} - T_{hit,low}) \tag{4.3}$$

In Figure 4.1 it can be seen that a hot utility needs to be provided to heat a cold process stream whose temperature is higher than $T_{h1s,max}$. A cold utility must be provided to cool a hot process stream whose temperature is lower than $T_{c3s,min}$.

4. Accessible and recoverable energy, Q_{acc} and Q_{rec}

Accessible energy can be defined as energy that is within the temperature limits of energy exchange. Recoverable energy is the maximum amount of energy that can be exchanged between the hot and the cold process streams.

Let

$Q_{acc,h}$ = Accessible energy from the hot process streams;

$Q_{acc,c}$ = Accessible energy to the cold process streams;

Q_{rec} = Recoverable energy; and

Q_{acc} = Accessible energy.

The accessible energy from the hot process streams is defined as:

$$Q_{acc,h} = \left| \sum_{i=1}^{n_h} \Delta H_{hi} \right| - \left| Q_{c,abs} \right| \tag{4.4}$$

The accessible energy to the cold process streams is defined as:

$$Q_{acc,c} = \left|\sum_{j=1}^{n_c} \Delta H_{cj}\right| - \left|Q_{h,abs}\right| \tag{4.5}$$

The accessible energy Q_{acc} is then the higher of the accessible energy from the hot process streams and the accessible energy to the cold process streams:

$$Q_{acc} = \max(Q_{acc,h}, Q_{acc,c}) \tag{4.6}$$

The recoverable energy Q_{rec} is the smaller of the accessible energy from the hot process streams and the accessible energy to the cold process streams:

$$Q_{rec} = \min(Q_{acc,h}, Q_{acc,c}) \tag{4.7}$$

The accessible energy is a "pool" of energy from which energy can be partially or completely recovered, depending on the thermodynamic constraints. The recoverable energy is the maximum amount of energy that can practically be withdrawn from the "pool" of energy. The annual cost of available energy is traded off against the annual capital cost in order to achieve the lowest possible network annual cost.

5. <u>Minimum utilities</u>, $Q_{h,min}$ and $Q_{c,min}$

Let

$Q_{c,min}$ = Minimum cold utility requirement and

$Q_{h,min}$ = Minimum hot utility requirement.

These quantities are defined as follows:

If $Q_{acc,h} > Q_{acc,c}$ then

$$Q_{h,\min} = Q_{h,abs} \tag{4.8}$$

and

$$Q_{c,\min} = Q_{acc,h} - Q_{acc,c} + Q_{c,abs} \tag{4.9}$$

If $Q_{acc,h} \leq Q_{acc,c}$ then

$$Q_{c,\min} = Q_{c,abs} \tag{4.10}$$

and

$$Q_{h,\min} = Q_{acc,c} - Q_{acc,h} + Q_{h,abs} \tag{4.11}$$

The minimum utility requirements $Q_{h,min}$ and $Q_{c,min}$ as defined above apply to conditions in which the heat recovery or minimum approach temperature is zero (in the Pinch Design Method). This is a condition of maximum energy recovery.

6. Number of units, n_{max}, $n_{hu,max}$, and $n_{cu,max}$

The view taken in this design method is that the minimum number of units does not guarantee global optimality of a network. Therefore, only a maximum number of units is prescribed and the designer is to choose the number of units which corresponds to the optimum network condition.

For a network involving n_h hot process streams and n_c cold process streams the maximum number of process exchangers n_{max} is defined as:

$$n_{\max} = n_h \times n_c \tag{4.12}$$

Assuming that a cold process stream can only need one hot utility, the maximum number of hot utility exchangers, $n_{hu,max}$,can be set at the number of cold process streams:

$$n_{hu,\max} = n_c \tag{4.13}$$

Assuming that a hot process stream can only need one cold utility, the maximum number of cold utility exchangers, $n_{cu,max}$, can be set at the number of hot process streams:

$$n_{cu,\max} = n_h \tag{4.14}$$

It must be indicated that the assumptions made here will affect network optimality because the limits set on the number of units are not based on any physical phenomenon or economic criterion. It is believed that the assumptions will reduce the number of candidate solutions. The objective of network design is to recover as much energy as possible at the lowest total annual cost possible. Design targets provide guidelines to achieve this objective. The targets used in this project are discussed below.

4.3. Network Design Targets

The targeting approach followed in this project is based on limiting values of the network annual cost. The upper limit of the network annual cost is the ceiling and the lower limit of the network annual cost is the floor. The objective is to design a network whose total annual cost is as far away as possible from the upper annual cost limit, and as close as possible to the lower annual cost limit. The cost limits are established on the basis of the stream and cost data defining the problem in question.

The global optimum for any network would serve as the ideal target, but it is not known either before or after network design. There is an uncertainty associated with a network design target, if the target is different from the global optimum. The reasons for this uncertainty are:

1. The heat transfer surface areas of the different matches are not known before network design;

2. The optimum number of units required is not known;

3. In this project the minimum approach temperature is allowed to assume a value of zero at the targeting stage in order to aim for maximum energy recovery. Actual network designs may not have an approach temperature of zero.

It is thus clear that a network design target is only an estimate. This estimate may not always be realistic. For this reason, it is important to set cost limits that can be used to guide the design. The network cost limits can only be useful if they are reproducible, irrespective of the targeting technique used. The terms that are used to describe the targeting process in this project are presented below.

1. Lower Cost Bound, LCB

The lower cost bound (LCB) is the lower limiting value of the network annual cost. It is defined in terms of maximum energy recovery. It is the minimum cost of energy:

$$LCB = C_{hu,\min} Q_{h,\min} + C_{cu,\min} Q_{c,\min} \tag{4.15}$$

The first product in Equation 4.15 is that of the unit cost of the cheapest hot utility and the minimum hot utility requirement. The second product is that of the unit cost of the cheapest cold utility and minimum cold utility requirement.

Obviously, the lower cost bound cannot be reached because it does not include capital costs. However, it is reproducible and it does not depend on any targeting method. It therefore serves as a reliable reference point. It is a limiting value.

2. Average cost target, ACT

The average cost target (ACT) is a weighted cost based on maximum energy recovery, the sum of the costs in each sub-matrix, and the total energy exchanged in each sub-matrix. It is defined as the sum of three products that are weighted costs associated with the process, hot utility, and cold utility sub-matrices.

In mathematical terms the average cost target is defined by Equation (4.16).

$$ACT = Q_{rec}\left(\frac{\sum_{i=1}^{n_h}\sum_{j=1}^{n_c} C_{a,ij}}{\sum_{i=1}^{n_h}\sum_{j=1}^{n_c} Q_{r,ij}}\right) + Q_{h,\min}\left(\frac{\sum_{i=n_h+1}^{n_{hu}}\sum_{j=1}^{n_c} C_{ce,ij}}{\sum_{i=n_h+1}^{n_{hu}}\sum_{j=1}^{n_c} Q_{hu,ij}}\right) + Q_{c,\min}\left(\frac{\sum_{i=1}^{n_h}\sum_{j=n_c+1}^{n_{cu}} C_{ce,ij}}{\sum_{i=1}^{n_h}\sum_{j=n_c+1}^{n_{cu}} Q_{cu,ij}}\right) \tag{4.16}$$

The first term on the right hand side of Equation 4.16 is a product of two quantities. The first factor is the recoverable energy. The numerator of the second factor is the sum of the capital costs $C_{a,ij}$ of matches in the process sub-matrix. The denominator of this factor is the sum of the heat loads Q_r in the process sub-matrix. The second factor is therefore a unit cost associated with the process sub-matrix. The numerator in this factor is the total cost of exchanging the total energy given as the denominator. The first term on the right hand side of Equation 4.16 is therefore the average process capital cost of recovering the maximum amount of energy.

The second and third terms on the right hand side of Equation 4.16 can be described in a similar manner. The numerator in the second factor of each of these terms is a sum of both the capital and energy costs $C_{ce,ij}$. The second term is an average cost of heat exchange associated with the hot utility sub-matrix. The third term is the average cost of heat exchange associated with the cold utility sub-matrix.

The average cost target will always be greater than the lower cost bound because it involves both the annual energy costs and the annual capital costs. The average cost target involves all feasible process matches, at their optimum conditions, in the process sub-matrix. This situation makes the average cost target superficial because the actual network may not involve all feasible process matches, and not all matches need be at their optimum conditions for a network to be globally optimal.

The average cost target is only a rough estimate. Because of the uncertainty associated with a network target mentioned at the beginning of this section, the average cost target is not a reliable reference for network evaluation. It may be smaller than the global optimum, in which case it may not be attainable. It may also be much larger than the global optimum, in which case it may misguide the designer. But it may also be close to the global optimum, in which case it is a meaningful target. Since the global optimum is not known, it is not easy to assess how meaningful the average cost target is.

3. <u>Cost Target Range</u>, CTR

It would be useful to know how far away the average cost target is from the lower cost bound. The cost target range (CTR) is defined as the difference between the average cost target and the lower cost bound:

$$CTR = ACT - LCB \tag{4.17}$$

The value of the cost target range gives an indication of the difference between the cost of a network design and the global optimum. If the cost of a network design is between the lower cost bound and the average cost target then the cost of the network design is within CTR units of the global optimum.

Since the targets set in this project are based on maximum energy recovery, any network design that falls in the cost target range will be accepted as good.

4. Network Cost Range, NCR

The network cost range is the difference between the network cost, NC, and the lower cost bound:

$$NCR = NC - LCB \tag{4.18}$$

The network cost range indicates how far the network cost is from the lower cost bound.

5. Cost Range Ratio, CRR

Network performance can be judged by comparing the network cost to the cost target. Alternatively, the network cost can be compared to the lower cost bound. It is also possible to compare the network cost to both the network cost target and the lower cost bound at the same time. Defining the cost range ratio, CRR, as the ratio of the network cost range to the cost target range can do this:

$$CRR = \frac{NCR}{CTR} \tag{4.19}$$

It is desirable that the cost range ratio be less than or equal to one, a condition in which the network cost is on target. Since a network target may not be realistic, a cost range ratio that is greater than one is not necessarily a reflection of a poor design. The use of the cost range ratio as a criterion for network performance is limited by the uncertainty associated with design targets.

A cost range ratio that is less than or equal to one means that the design is on target, and that the network cost is within the cost target range of the global optimum.

6. Upper Cost Bound, UCB

Another way of judging the performance of a network design is to determine cost savings. This is done, in this project, by first defining a cost ceiling on the basis of which the cost savings can be estimated. The cost ceiling is simply the maximum allowable cost any network can have.

The upper cost bound (UCB) is the cost of a network which has utility matches only, that is, a network in which there are no process matches, and therefore there is no energy recovery. This is a condition of maximum energy consumption, a direct opposite of the condition of minimum energy consumption. The upper cost bound is defined as:

$$UCB = \sum_{j=1}^{N_c} C_{hu,j} Q_{hj} + \sum_{i=1}^{N_h} C_{i,cu} Q_{cj} \tag{4.20}$$

Unless some utility matches are prohibited, it is not easy to see how a network cost that is higher than the upper cost bound can be justified. The difference between the network cost and the upper cost bound gives an indication of the cost savings.

7. Network Performance Index, NPI

The network performance index is a comparison of the network cost to the upper cost bound. It is defined by:

$$NPI = \frac{NC - LCB}{UCB - LCB} \tag{4.21}$$

The network performance index indicates the cost savings relative to the condition of no energy recovery. Since no cost savings on the lower cost bound can be achieved, the lower cost bound is subtracted from the network cost and the upper cost bound. Under normal circumstances the network performance index will have a value that is between zero and one. It is desirable that the value of the network performance index be as close as possible to zero. It will never be zero because the network cost will always be greater than the lower cost bound. If the value of the network performance index is one, then the network cost is equal to the upper cost bound and no cost savings are achieved.

The cost limits discussed above are illustrated in Figure 4.2. In Figure 4.2 the lowest level is the lower cost bound. A network cost cannot reach this level. The next higher cost level is the average cost target. This is the network design target. It is desirable to design a network whose cost is less than or equal to this target. A network whose cost is in the region between the lower cost bound and the average cost target is good.

Most networks will lie in the region between the average cost target and upper cost bound. Networks that are closer to the upper cost bound than they are to the average cost target are not economically attractive. The worst design case can occur if the network cost is higher than the upper cost bound. This condition can occur if at least one of the matches in the network involves a very small temperature driving force. If this driving force approaches zero, the heat transfer surface area approaches infinity. Under these conditions the capital cost can be very high.

The sketch shown as Figure 4.2 represents the search space in which the best network is to be found. The search space can contain a large number of feasible designs. The use of network design targets in network evaluation is explored in the following section.

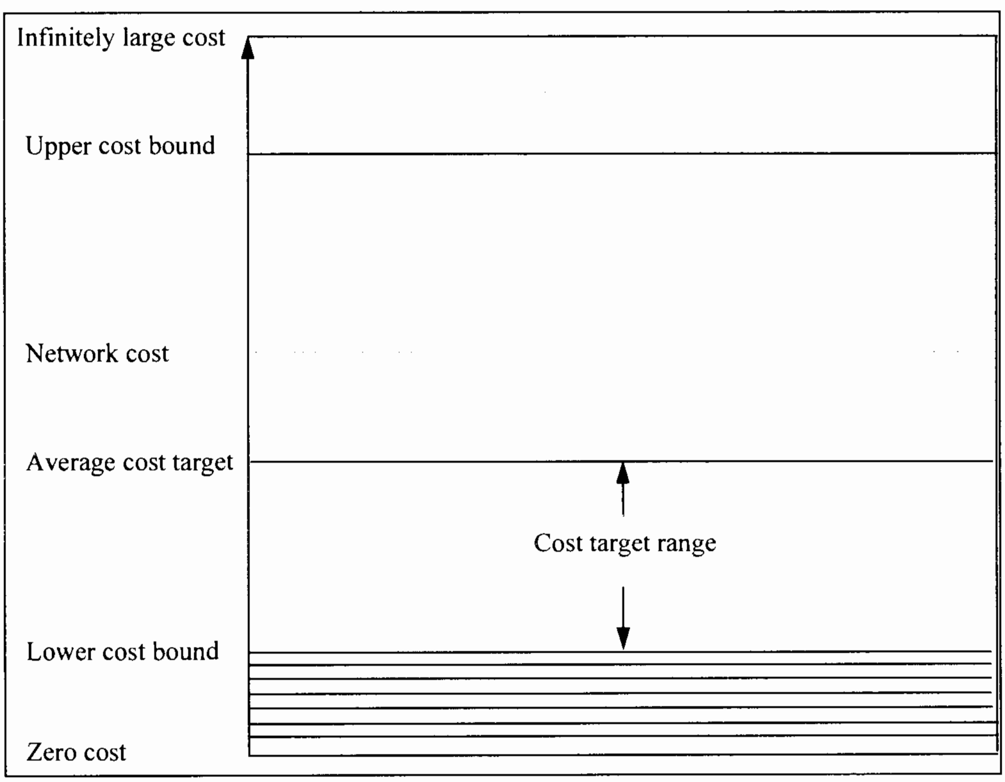

Figure 4.2: Network cost target and limits.

4.4 Evaluation of Network Performance

The lower cost bound and the upper cost bound are reproducible reference points that can be used to evaluate network performance. Network costs should be as close as possible to the lower cost bound. The thorny issue is to specify just how close a network cost should be to the lower cost bound. This issue is complicated by the fact that there is no known relation between the minimum annual cost of utilities and the global optimum or the network annual cost. Ideally, the network cost target should be the global optimum.

Since the global optimum is not known, a different performance standard is necessary. However, this performance standard should be determined by, or related to, the individual network problem in question, just like the global optimum.

It is tempting to think of a certain percentage of the upper cost bound as the maximum allowable value that defines a near optimal design. This approach, though, does not take into account the fact that each network is different. The optimum amount of energy that can be recovered depends on the configurations of the individual streams. Therefore, no single percentage of the upper cost bound can serve as a consistent performance criterion for all cases of network designs. Thus, any performance criterion chosen for network evaluation should be derived from the stream and cost data that define the problem under study. This matter, though crucial, falls outside the scope of this project.

Although the network performance index and the cost range ratio give an indication of the performance of a network design, there are no obvious values of these quantities that can be used to define a near optimal network. The maximum cost savings that can possibly be achieved for any given problem are determined by the nature of the stream and cost data. Hence, any criteria that can be used to evaluate a network design must be derived from, or related to, individual problems.

In this study the network performance index and the cost range ratio will be determined for each problem. An investigation will be made into a possible relation between the network performance index, cost range ratio, lowest network cost reported in the literature, and the lowest cost target reported in the literature.

Example 4.1: Determination of the network cost target and limits.

Each of the quantities defined above, except the network cost range, network performance index, and the cost range ratio, is calculated. The cost target range, network performance index, and the cost range ratio can only be calculated if the network has been designed and its cost calculated. The maximum number of units will be determined in Chapter 5, which deals with network optimisation.

The targeting concepts discussed above are illustrated with a network problem (Table 4.2) that was taken from Yee and Grossmann (1990). The problem involves two hot process streams, two cold process streams, one hot utility, and one cold utility.

Table 4.2: Stream data for Example 4.1 (Yee and Grossmann, 1990).

Stream	T_S (K)	T_t (K)	F_{cp} (kW/K)
H1	443	333	30
H2	423	303	15
C1	293	408	20
C2	353	413	40
HU	450	450	-
CU	293	313	-

<u>Cost data</u>

U = 0.8 ($kWm^{-2}K^{-1}$) for all matches except ones involving steam.

U = 1.2 ($kWm^{-2}K^{-1}$) for matches involving steam.

Annual cost = 1000 × [area (m^2)]$^{0.6}$ for all exchangers except heaters.

Annual cost = 1200 × [area (m^2)]$^{0.6}$ for heaters.

Hot utility cost = 80 \$/(kW.yr).

Cold utility cost = 20 \$/(kW.yr).

The different quantities to be calculated are listed below.

1. *Absolute hot utility requirement*

The highest supply temperature of the hot process stream is 443 K. There is no cold process stream whose target temperature is higher than 443 K. Therefore, there is no absolute hot utility requirement:

$$Q_{hu,abs} = 0$$

2. *Absolute cold utility requirement*

The lowest cold stream supply temperature is 293 K. There is no hot process stream whose target temperature is lower than 293 K. Therefore, there is no absolute cold utility requirement:

$$Q_{cu,abs} = 0$$

3. *Accessible energy and recoverable energy*

$$Q_{acc,h} = F_{h1} (T_{h1s} - T_{h1t}) + F_{h2} (T_{h2s} - T_{h2t}) - Q_{c,abs}$$

$$= 30 (443 - 333) + 15 (423 - 303) - 0$$

$$= \underline{5100 \text{ kW}}$$

$$Q_{acc,c} = F_{c1} (T_{c1t} - T_{c1s}) + F_{c2} (T_{c2t} - T_{c2s}) - Q_{h,abs}$$

$$= 20 (408 - 293) + 40 (413 - 353) - 0$$

$$= \underline{4700 \text{ kW}}$$

$$Q_{acc} = \max (Q_{acc,h} , Q_{acc,c})$$

$$= \max (5100 \text{ kW} , 4700 \text{ kW})$$

$$= \underline{5100 \text{ kW}}$$

$$Q_{rec} = \min (Q_{acc,h} , Q_{acc,c})$$

$$= \min (5100 \text{ kW} , 4700 \text{ kW})$$

$$= \underline{4700 \text{ kW}}$$

4. *Minimum utility requirements*

Since the accessible energy from the hot streams, $Q_{acc,h}$, is greater than the accessible energy to the cold streams, $Q_{acc,c}$, the minimum hot utility requirement is given by:

$$
\begin{aligned}
Q_{h,min} &= Q_{h,abs} \\
&= \underline{0 \text{ kW}}
\end{aligned}
$$

The cold utility requirement is then given by:

$$
\begin{aligned}
Q_{c,min} &= Q_{acc,h} - Q_{acc,c} + Q_{h,abs} \\
&= 5100 - 4700 + 0 \\
&= \underline{400 \text{ kW}}
\end{aligned}
$$

Selection Matrix

All possible matches that can be made are put in the Selection Matrix. The Selection Matrix derived from Table 4.2 is shown in Table 4.3.

Table 4.3: Selection Matrix derived from Table 4.2 showing the optimum match costs and heat loads of the possible matches.

	C1	C2	CU
H1	C_{ij} = 11 129 Q_r = 2300	C_{ij} = 388 Q_r = 2400	C_{ce} = 76 953 Q_{cu} =3300
H2	C_{ij} = 16 224 Q_r = 1800	C_{ij} = 16 191 Q_r = 1029	C_{ce} = 46 945 Q_{cu} = 1800
HU	C_{ce} = 191 662 Q_{hu} = 2300	C_{ce} = 201 623 Q_{hu} = 2400	

In Table 4.3 all the process matches have been optimised for the first time and no matches have been placed in the network.

5. *Lower Cost Bound*

LCB $= (80 \times 0) + (20 \times 400)$

$= \underline{\$\ 8000\ /\ \text{year}}$

6. *Average Cost Target*

ACT $=$ $4700[(11129+21388+16224+16191)/(2300+2400+1800+1029)]$

$+ 0[(76953+46945)/(3300+1800)] + 400[(191662+201623)/(2300+2400)]$

$=$ $4700(64932/7529) + 0(123898/5100) + 400(393285/4700)$

$=$ $\underline{\$\ 74\ 005\ /\ \text{year}}$

7. *Cost Target Range*

CTR $= 74\ 005 - 8000$

$= \underline{\$\ 66\ 005\ /\ \text{year}}$

8. *Upper Cost Bound*

UCB $= 76\ 953 + 46\ 945 + 191\ 662 + 201\ 623$

$= \underline{\$\ 517\ 183/\text{year}}$

Summary

Targeting is the process whereby minimum utility and capital cost requirements are determined ahead of network design. Network design targets are used to guide the design process.

At the targeting stage the optimum heat transfer surface area of each unit is not known. Therefore design targets may not be consistently close to the global optima. For this reason, design targets may not be reliable reference points for the evaluation of network performance. They may be less than the global optimum and may therefore not be achievable. They may also be much larger than the global optima and in this case may lead to insufficient cost savings. A target may be close to the global optimum; in this case the target is meaningful. It is not easy to establish how close a design target is to the global optimum because the global optimum is not known. Therefore, the targeting procedure used in this study includes the upper and lower cost bounds for each network considered.

The objective of network design is to achieve a network cost that is as close as possible to the lower cost bound. A network that meets this condition can be said to be at least near optimal. A difficulty was experienced in specifying how close a network annual cost should be to the lower cost bound. The source of this difficulty is the fact that a problem-specific evaluation criterion could not be established. A problem-specific criterion is necessary because the global optimum for each network problem is determined by the particular stream and cost data defining the problem.

In the absence of an appropriate evaluation criterion it was decided to investigate any possible relation among the network performance index, cost range ratio, lowest network costs reported in the literature, and the lowest cost targets reported in the literature.

CHAPTER 5

Network Optimisation

Introduction

In the history of heat exchanger network synthesis many techniques have been developed to design networks. These techniques are different ways of solving the same problem. Diverse as they may be, all of them perform the same task: selection of pairs of streams that exchange energy, and ordered placement of the matches in the network. This process involves many possible pairs of streams and arrangements of exchangers. The critical task is to select stream pairs and then place matches in the network in such a way that the total annual cost is minimised. These two factors, stream selection and orderly match placement, determine the network cost.

What makes stream matching a challenge is the fact that, in general, initial match placements affect successive match placements in terms of energy recovery. The effect of initial match placements on successive ones is poorly understood. Designers have faced this aspect of network design with heuristics, logic, or mathematical search techniques. Yet it has never been obvious which matches should be placed before others. Because of this uncertainty networks generated have not been consistently near optimal.

Irrespective of the technique used to design a network, match sequencing is an integral part of the stream matching process and it has a cost implication. Once designed and implemented, the network lives with the cost implication for the rest of its lifetime. This means that inefficient network designs incur a lifetime penalty. This is to be avoided by generating efficient, low-cost networks.

The purpose of this chapter is to explore a way of matching streams in such a way that the network designs are consistently near optimal. The steps taken to achieve this objective are match sequencing and evolutionary development. Match sequencing is the process of selecting matches and placing these matches in a network in an orderly cost-saving manner. Evolutionary development is the improvement of a preliminary or existing network into a cheaper final structure. These two steps are discussed below, in sections 5.1 and 5.2, respectively.

5.1 Match Sequencing

The nature of chemical processes is such that matches can only be arranged in a certain order. That is, it is unlikely to have all matches placed in a network at the same time. The order in which matches are placed in a network has a direct impact on energy recovery, and consequently, on the operating cost as well as on the capital cost.

Every network design technique is essentially a match sequencing process. In mathematical techniques the sequencing process is performed automatically, by a computer, on the basis of rules specified by the designer as equations and conditions describing the heat exchange process. In insight-based techniques the sequencing process is performed by the designer on the basis of rules specified by the designer as equations, logical reasoning, past experience, and/or judgement.

Any network design technique is essentially a way of selecting a number of matches to be placed in a network out of a large number of possible matches.

In this section an attempt is made to examine different cases in which a choice is to be made between matches competing for a position in the network. Two core considerations in network design are the consumption of utilities and the allocation of temperature driving forces to heat loads.

Hot utilities tend to carry the largest weight of the network cost. This is because they involve capital costs as well as energy expenses. Although cold utilities also involve both capital and energy costs, they tend to be less expensive than hot utilities. If the temperature driving forces are properly distributed, the cost associated with process exchangers tends to be the smallest fraction of the network cost, compared with the costs of the hot and the cold utilities. It is only logical to consider these facts as guidelines and to prioritise them when selecting and placing matches in a network.

The approach adopted in this section is to give the hot utilities the highest priority. This means that cold process streams will be given preferential treatment. After hot utilities priority will be given to cold utilities. Lastly, process matches will be given the least priority.

The objective is to use hot process streams to heat cold process streams if the process matches are cheaper than the corresponding hot utility matches are. This, in turn, will tend to use up less cold utilities as hot process streams will be cooled by cold process streams. Each match will be evaluated against other options before selection and placement in the network. This suggests the possibility of placing utility matches before process matches. In other words, the approach adopted here allows for the integration of utilities.

An important observation made during match optimisation is that, for any match, optimality is favoured by energy exchange between the hottest end of the hot stream and the coldest end of the cold stream. This fact will influence the structure of the stream-matching algorithm.

Network design is about match choices. These choices directly affect network optimality. It is therefore worthwhile to examine situations in which matches compete for a position in the network. In doing this it is necessary to consider the priorities mentioned above as well as the factors that influence match optimality, namely, stream properties, process conditions, and economics.

5.1.1 Match choices

A number of situations that can arise during network design are discussed below. Each situation is intended to illustrate the nature of decisions that need to be taken in match selection. Before these cases of match choices are discussed, a mathematical situation that justifies match evaluation before selection is presented.

Mathematical justification for match evaluation before selection

Suppose either a hot process stream or a hot utility stream can heat a cold process stream. If the hot process stream were used, the cost of the match would be given by C_p as shown in Equation 5.1:

$$C_p = C_{0,p} + C_{1,p}\left[\frac{(h_c + h_h).Q}{(h_h.h_c).\Delta T_{LM,p}}\right]^{b_p} \tag{5.1}$$

where Q is the energy exchanged, and the subscript p stands for a process match.

On the other hand, if the hot utility stream is used to heat the cold process stream, C_{ce} as shown in Equation 5.2 will give the cost of the resulting match:

$$C_{ce} = C_{0,hu} + C_{1,hu}\left[\frac{(h_c + h_{hu}).Q}{(h_{hu}.h_c).\Delta T_{LM,hu}}\right]^{b_{hu}} + Q.C_{hu} \tag{5.2}$$

If C_p is less than or equal to C_{ce} then the match between the hot process stream and the cold process stream could be a reasonable choice. However, there is no guarantee that C_p will always be less than or equal to C_{ce}. Examination of Equations 5.1 and 5.2 illustrates this point.

Although the exchanger heat load in each of these equations is the same, it is not obvious that C_p will always be less than or equal to C_{ce}. Even if it is assumed that $\Delta T_{LM,p}$ is greater than $\Delta T_{LM,hu}$ quite a number of parameters need to be considered before the cheaper of the two possible matches is known. The parameters that need to be known are: $C_{0,p}$; $C_{1,p}$; h_c; h_h; b_p; $C_{0,hu}$; $C_{1,hu}$; h_{hu}; b_{hu}; and C_{hu}. There is no known physical or economic law that relates any of these parameters: they are independent of one another. For instance, there is no law that says b_p must always be equal to b_{hu}, less than b_{hu}, or greater than b_{hu}.

Therefore, the choice of the cheaper match will only be made when all the parameters are known. Whether C_p is greater than, equal to, or less than C_{ce} is also not necessarily a sufficient condition for choosing the cheaper match. The other matches that remain after the match has been chosen also need to be considered. Before the match is selected it is necessary to predict how the remaining possible matches will be affected by the particular match choice. It is necessary to know whether the choice of a given match will result in a higher or lower network cost. This is a difficult decision to make.

Different situations in which a match is selected are shown qualitatively below. The insight gained is to be used in developing the stream matching procedure to be used in this project.

<u>Case 1</u>: One hot process stream and one cold process stream of equal heat load.

This situation is illustrated in Figure 5.1a. Utilities HU and CU are provided.

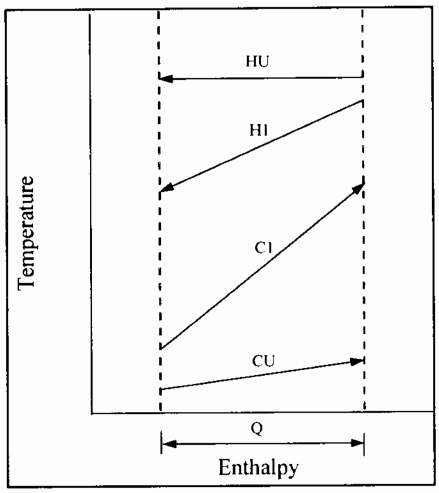

Figure 5.1a: Heat exchange involving one hot process stream and one cold process stream.

Figure 5.1a depicts a situation in which the hot process stream can transfer all of its energy to the cold process stream. At a first glance a designer might match H1 with C1 in order to save on the cost of utilities. This choice seems to make sense because there will be only one heat exchanger and no utilities consumed.

However, it may also happen that the cost of the process exchanger is high and the heat transfer coefficients of H1 and C1 are much smaller than those of the utility streams HU and CU. Under these conditions it may be economical to use the hot utility to heat C1 and the cold utility to cool H1.

Therefore, a meaningful way of handling the situation is to compare the cost of the process exchanger [H1,C1] to the total cost associated with the complete use of the utilities. Whichever cost is smaller would be the best match choice.

Case 2: One hot process stream and two cold process streams - all the process streams have equal heat loads.

This situation is similar to the previous one, except that there is one more cold process stream. This means that the two cold process streams are competing for energy from the hot process stream, as shown in Figure 5.1b.

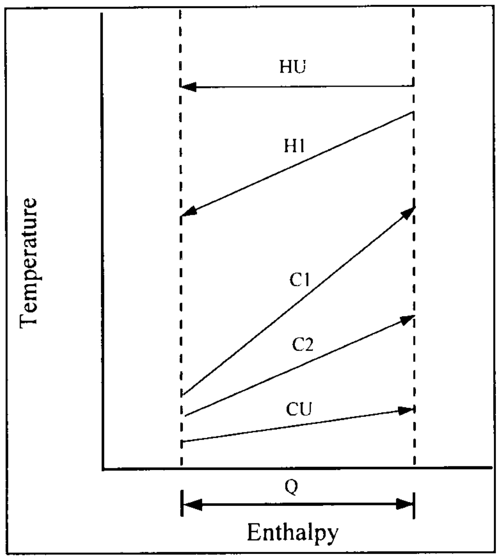

Figure 5.1b: Heat exchange involving one hot process stream and two cold process streams.

One of the cold process streams will be matched with a hot utility stream because the energy content of the hot process stream can only be transferred to one cold process stream. The question is which of the two cold process streams should be matched with the hot process stream.

One designer may choose the matches [H1,C1] and [HU,C2], and another designer may choose [H1,C2] and [HU,C1]. The best approach is to compare the total cost associated with the following options:

1. Matches [H1,C1] and [HU,C2], and the cost of the hot utility;
2. Matches [H1,C2] and [HU,C1], and the cost of the hot utility; and
3. Matches [H1,CU], [HU,C1], [HU,C2], and the cost of utilities.

This is necessary because the overall impact of the variables and process conditions on the total cost differs from one match to another, and is not always predictable. It is for this reason that the use of heuristics is not likely to consistently give good results. Some quantitative and reliable evaluation of the match options is necessary before match placement.

Case 3: Two hot process streams and two cold process streams - all streams have equal heat loads.

A situation that may appear to have an obvious solution is illustrated in Figure 5.1c. All the process streams have equal heat loads.

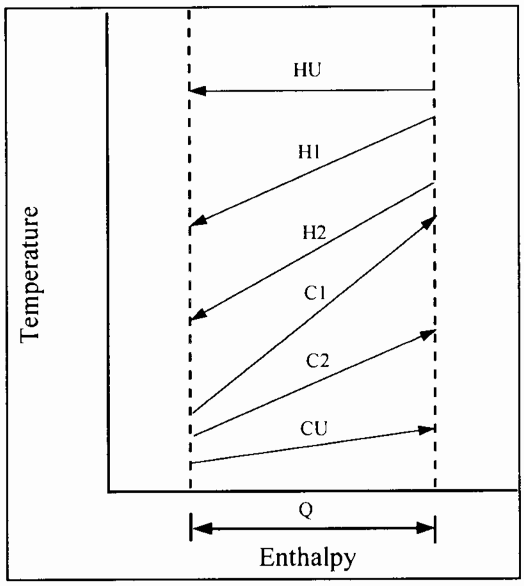

Figure 5.1c: Heat exchange involving two hot process streams and two cold process streams.

It would seem logical to match H1 with C1, and H2 with C2, because this choice seems to be compatible with the proportionate distribution of temperature driving forces among the units. Again, this may not always be the best solution because the materials of construction, and the heat transfer coefficients may differ from one match to another. For instance, the match between H1 and C2, and the match between H2 and C1, may be more economically meaningful than the seemingly obvious options. Furthermore, a combination of process and utility matches need also be evaluated. Even the seemingly remote possibility of using utilities only must also be evaluated.

By now it should be clear that each network design problem is different and can better be handled by considering its own merits.

The match cases presented above have been oversimplified to illustrate the selection process. For heat exchange situations involving different heat loads, stream properties, process conditions, number of streams, exchanger costs, and energy costs the decision-making process becomes more difficult. This situation is further complicated by the fact that a match placement may affect successive matches. The general approach to match selection is explained next.

Case 4: General match selection stage.

A general stage during stream matching is depicted in Figure 5.1d, showing possible matches in a Selection Matrix. The consequences of matching the cold process stream C3 are examined below.

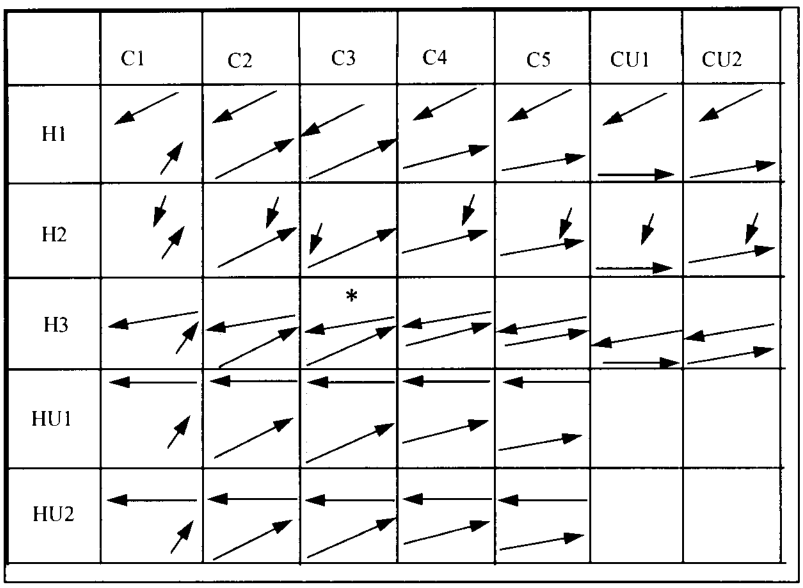

Figure 5.1d: Selection Matrix during match selection - match possibilities for C3 are examined.

In Figure 5.1d the supply temperature of hot process stream H1 is greater than the supply temperature of hot process stream H2. The supply temperature of hot process stream H2 is in turn higher than the supply temperature of hot process stream H3. Hot stream H3 can completely satisfy the energy requirement of C3. Each of H1 and H2 can partially meet the energy requirement of C3. Each of hot utilities HU1 and HU2 can completely meet the energy requirement of C3. Therefore, the energy requirement of C3 can be met in a number of ways. The question is which option is best.

To answer this question two factors need to be considered, and these factors are the condition of the match chosen and the effect of this match on successive matches. Successive matches that will be affected directly are those in the same row as the hot stream and those in the same column as the cold stream. The match chosen will affect the heat loads and the temperature driving forces of these matches. The other remaining matches may be affected indirectly.

If match [H3,C3] is chosen the hot process stream will be eliminated from row H3 and the cold process stream will be eliminated from column C3. This will happen because H3 and C3 have equal heat loads.

Chances that the cold process streams in row H3 will receive energy from a hot process stream decrease. Each of cold process streams C1, C2, C4 and C5 can no longer receive energy from H3. These cold process streams now compete for energy from hot process streams H1 and H2. Chances that the hot process streams in column C3 will transfer their energy to a cold process stream also decrease. Streams H1 and H2 can no longer transfer their energy to C3.

It can be seen that, with respect to individual streams, the selection of a match tends to decrease energy exchange possibilities. The effect of placing a match tends to propagate throughout the Selection Matrix. For instance, before selection of any match, C1 could receive energy from H1, H2, or H3. Relative to C1 the best match could be [H3,C1]. In addition to this it could just happen that [H3,C1] must be one of the matches in order for the network to achieve global optimality. But because match [H3,C3] has already been selected, it is no longer possible to have [H3,C1]. This implies that it is no longer possible to achieve global optimality.

The conclusion to be drawn here is that selection of a match decreases the match possibilities for the remaining streams. In addition to this is the fact that energy exchange between any two remaining streams may become more severely constrained by temperature. The decrease in match possibilities due to match selection is unavoidable. The temperature constraints imposed by one match on successive matches are a critical aspect of network design. Since it is impractical to design all possible networks for a given problem this situation can only be resolved by a judicious choice of matches. In this project an attempt was made to achieve such a choice by evaluating each match before placement in the network.

Match evaluation involves comparison of all matches involving the stream whose energy requirement is to be satisfied. Important considerations are the supply and target temperatures of the stream, the match unit cost of the match possible, the energy exchanged, and the effect of the match on the remaining matches. This process is described later in this chapter as a procedure for stream matching.

In this project the quality of a network is judged by the cost. It is therefore important to define the objective function to be optimised. This is done in the next section.

5.1.2 The objective function

If there are n_{h-c} process exchangers, n_{hu-c} hot utility exchangers, and n_{h-cu} cold utility exchangers then the sum of the annual capital costs C_c and the sum of the energy costs C_e are defined as follows:

$$C_c = \sum_{k=1}^{n_{h-c}} \delta_k (C_{0,k} + C_{1,k} A_k^{b_k}) + \sum_{k=1}^{n_{hu-c}} \delta_k (C_{0,k} + C_{1,k} A_k^{b_k}) + \sum_{k=1}^{n_{h-cu}} \delta_k (C_{0,k} + C_{1,k} A_k^{b_k}) \tag{5.3}$$

$$C_e = \sum_{i=1}^{n_h} Q_{cu,i} C_{cu,i} + \sum_{j=1}^{n_c} Q_{hu,j} C_{hu,j} \tag{5.4}$$

The objective function, C_{tot} is defined as:

$$C_{tot} = C_c + C_e \tag{5.5}$$

The objective is to minimise the total cost subject to thermodynamic constraints and any restrictions imposed on the problem. Before matching the streams it may be necessary to re-arrange the streams given in the stream data. This is the first stage of network design in this project and it is intended to promote cost reduction in the successive stages of the network design process. Stream arrangement is discussed next.

5.1.3 Stream arrangement

The purpose of stream arrangement is to establish a match sequencing order that is likely to lead to a near optimal final network. Stream arrangement may involve stream fragmentation before pairing. Streams may be fragmented into smaller segments in order to enhance energy recovery. The idea is to ensure preferential matching and to avoid certain matches by restraining the inlet and outlet temperatures of the process streams. This is possible because the relative magnitudes of the supply and target temperatures of the hot and cold streams are the major determinants of the extent of energy recovery between the two streams.

The general approach is to fracture the streams in such a way that the hottest fragments of the hot process streams exchange energy with the hottest fragments of the cold streams.

Streams are fractured on the basis of the supply and target temperatures of the process streams. Cold process streams are fractured, where possible, at the target temperatures of cold process streams that are lower than the highest target temperature of the cold process stream, and at supply temperatures of the cold process streams that are higher than the lowest supply temperature of the cold process streams. This situation is shown in Figure 5.2a.

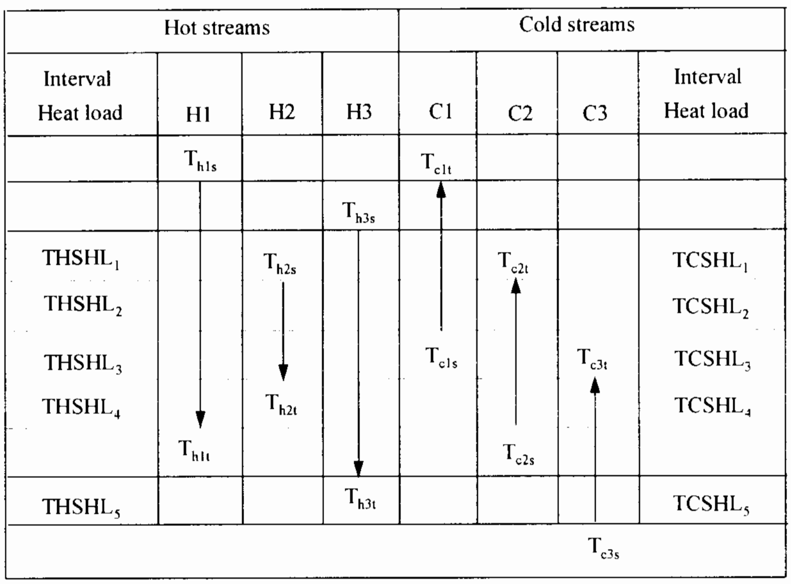

Figure 5.2a: Stream arrangement showing temperatures at which cold process streams are fractured.

In Figure 5.2a the highest target temperature of the cold streams is T_{c1t}. The second highest cold stream target temperature is T_{c2t} and the lowest cold stream target temperature is T_{c3t}. Cold process stream C1 is fractured at temperature T_{c2t}. Cold process stream C2 is fractured at temperatures T_{c1s} and T_{c3t}. Cold process stream C3 is fractured at T_{c2s}. This stream fragmentation is performed to control the stream matching process.

The stream fragments whose temperature is equal to or higher than T_{c2t} are allowed to exchange energy first; this is the first subset of stream fragments. The total heat load of fragments of hot process streams whose temperature is higher than or equal to T_{c2t} is $THSHL_1$

(Total Hot Stream Heat Load 1). The total heat load of the fragments of cold process streams whose temperature is equal to or larger than T_{c2t} is $TCSHL_1$ (Total Cold Stream Heat Load 1). The intention here is to transfer energy from the hottest fragments of the hot process streams to the hottest fragments of the cold process streams. The fragmentation process is meant to ensure that the energy requirements of the hottest cold process streams are met before energy from the hottest hot process streams is transferred to colder cold stream fragments.

The supply and target temperatures of the cold process streams are used to define temperature intervals in which energy is preferentially exchanged. The heat loads of like process streams (hot or cold) are added. In the temperature interval starting from T_{c1s} to T_{c2t} the total heat load of the hot process streams is $THSHL_2$, and the total heat load of the cold process streams is $TCSHL_2$. The rest of the intervals are defined in a similar manner, as shown in Figure 5.2a. When the heat load of a stream fragment is too small for practical purposes, for example 0.1 kW, the stream is not fragmented in the temperature interval.

In some cases a large cold process stream has to be heated by a number of smaller hot process streams. In this situation the cold process stream is fractured, where possible, at the target temperatures of the hot process streams that are higher than the smallest target temperature of the hot process streams. Once this has been done the same procedure as described above is followed. The way in which the cold process stream is fractured is illustrated in Figure 5.2b. The cold process stream C1 is fractured at T_{h1t} and T_{h2t}.

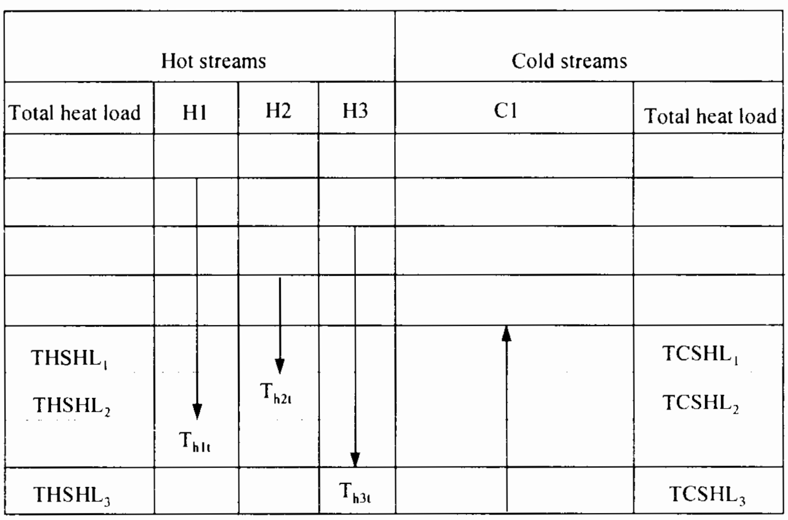

Figure 5.2b: Stream arrangement showing one large cold process stream and how it is fractured.

The stream data given in Table 4.2 of Chapter 4 will now be used to illustrate the stream arrangement process.

Example 5.1: Stream arrangement

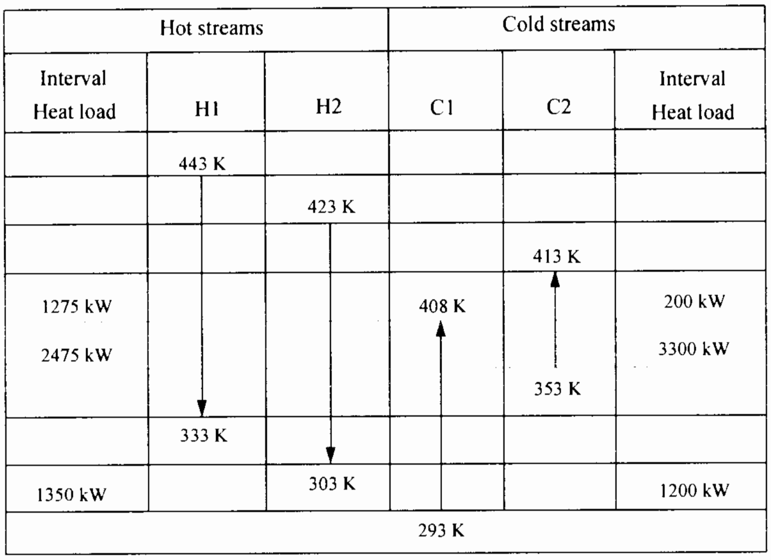

Figure 5.3: Dotted lines show temperatures at which the cold process streams are fractured.

In Figure 5.3 it can be seen that cold process stream C1 can be fractured at 353 K, and C2 can be fractured at 408 K. As a result there is now a total of four cold process streams, two stream fragments from each of C1 and C2.

Once the stream arrangement process is finished the streams are matched. The match selection procedure is discussed next.

5.1.4 Match selection procedure

The considerations that constitute the major elements of the match selection process are:

1. The energy requirements of the cold process streams are given the highest priority;

2. For any two streams selected, match optimality is favoured by energy exchange between the hottest end of the hot process stream and the coldest end of the cold process stream;

3. The cost of exchanging one unit of energy per unit time, the match unit cost, is used to evaluate each match before placement in the network; and

4. The effect of the match chosen on the remaining matches.

The first consideration is intended to ensure the minimum hot utility consumption, subject to individual match optimality. The temperature intervals established through the stream arrangement process are used to ensure that energy from the hotter fragments of the hot process streams is transferred to cold process streams in the same temperature interval before it can be transferred to cold process streams in lower temperature intervals.

The second consideration is used to determine the order in which process streams of one type will be matched. A process stream may have to exchange energy with a number of process streams of the opposite nature before its energy requirement is satisfied. This situation can be illustrated with the aid of a sketch, Figure 5.4a.

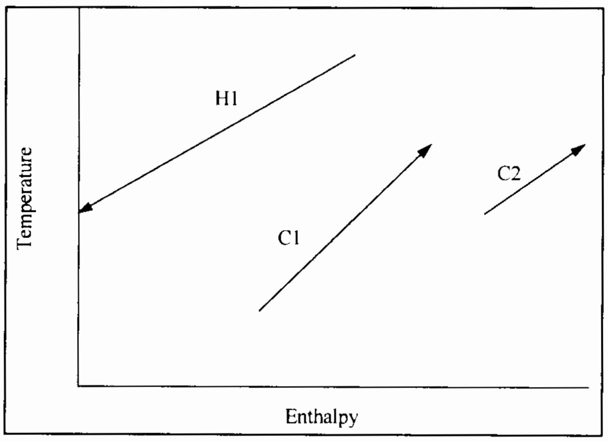

Figure 5.4a: Two cold process streams to be matched with a hot process stream.

In Figure 5.4a the hot process stream H1 can exchange energy with either C1 or C2. The question is which cold stream should be matched with H1 first. If C1 is matched with H1 first then the result is the enthalpy diagram shown in Figure 5.4b. If C2 is matched with H1 first the result is shown in Figure 5.4c.

The difference between Figures 5.4b and 5.4c is that energy recovery in Figure 5.4b is incomplete whereas energy recovery in Figure 5.4c is complete. In Figure 5.4b a hot utility is required to heat cold process stream C2 from T_1 to T_{c2t}. A cold utility is required to cool hot process stream H1 from T_2 to T_{h1t}. In Figure 5.4c there is no utility requirement. This simple example shows that if it is known that match optimality is favoured by energy exchange between the hottest end of the hot stream and the coldest end of the cold stream, matches can be sequenced in a manner that enhances energy recovery.

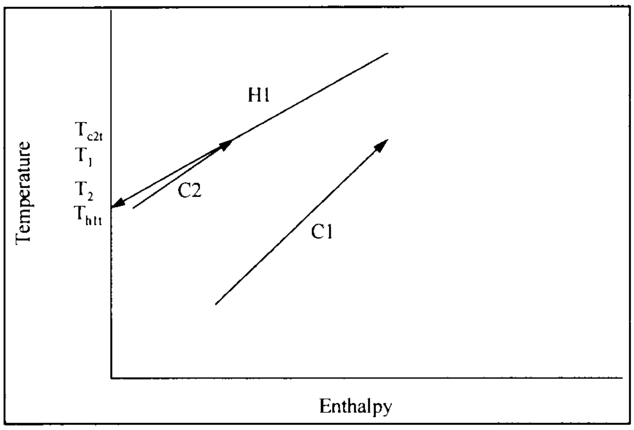

Figure 5.4b: Case in which the first match involves hot process stream H1 and cold process stream C1.

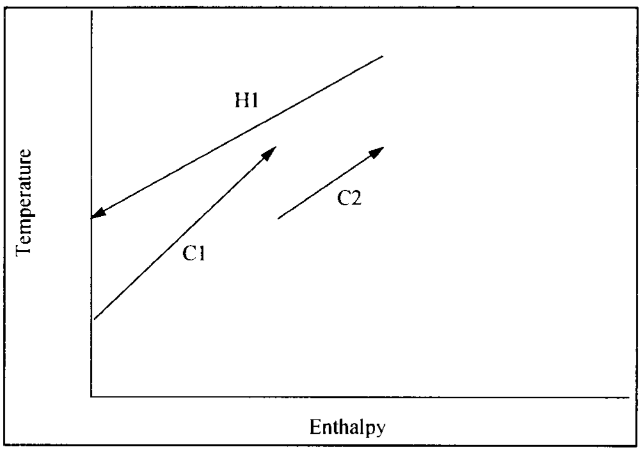

Figure 5.4c: Case in which the first match involves H1 and C2.

The third consideration is used to economically justify the choice of one possible match over others.

The fourth consideration is intended to ensure that the match chosen does not adversely affect the remaining possible matches. Matches are selected from the Selection Matrix when all the possible matches are at their optimum conditions.

The steps followed to select a match are presented below. A sketch, Figure 5.5a, has been included to illustrate the stream matching steps given.

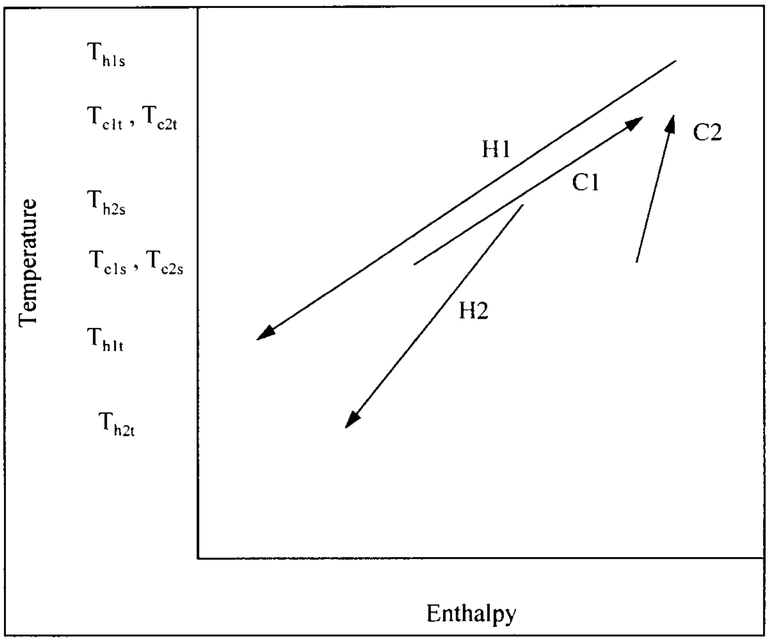

Figure 5.5a: Sketch used to illustrate match selection steps

a). Selection of the cold process stream

i. *Identify the cold process stream that has the highest target temperature.*

The intention of this step is to consider the use of hot process streams to meet the energy requirements of the cold process stream before using hot utilities. This is an attempt to minimise the consumption of hot utilities, subject to match optimality.

In Figure 5.5a both cold streams have the same target temperature. Because both streams cannot be matched simultaneously with the same hot stream, this situation needs to be resolved. The next step is meant to resolve the situation.

ii. *If two or more cold process streams have the same highest target temperature, choose the stream that has the lowest heat capacity flowrate.*

For two cold streams that have different heat capacity flowrates, the stream that has the smaller heat capacity flowrate has a smaller heat load in the same temperature interval. It therefore takes a smaller amount of energy, removed from the hot process stream, to get the smaller cold process stream outside the temperature range of energy exchange with that hot process stream. If there are no more hot process streams that can transfer energy to this smaller cold process stream then a hot utility has to be supplied. It is therefore necessary to match the smaller of two cold process streams first in order to reduce hot utility consumption.

In Figure 5.5a cold process stream C1 has a higher heat capacity flowrate compared to C2. Therefore C2 would be the first cold process stream to be matched with the hot streams. If this is done, Figure 5.5a shows that there will be no hot utility requirement since the residual of hot process stream H1 will still be large enough to meet the energy requirement of cold process stream C1.

Suppose C1 were the first cold process stream to be matched with H1. There is a possibility that the residual of H1 would have a supply temperature that is too low to allow for an energy transfer that completely meets the requirements of cold process stream C2. This situation is illustrated in Figure 5.5b.

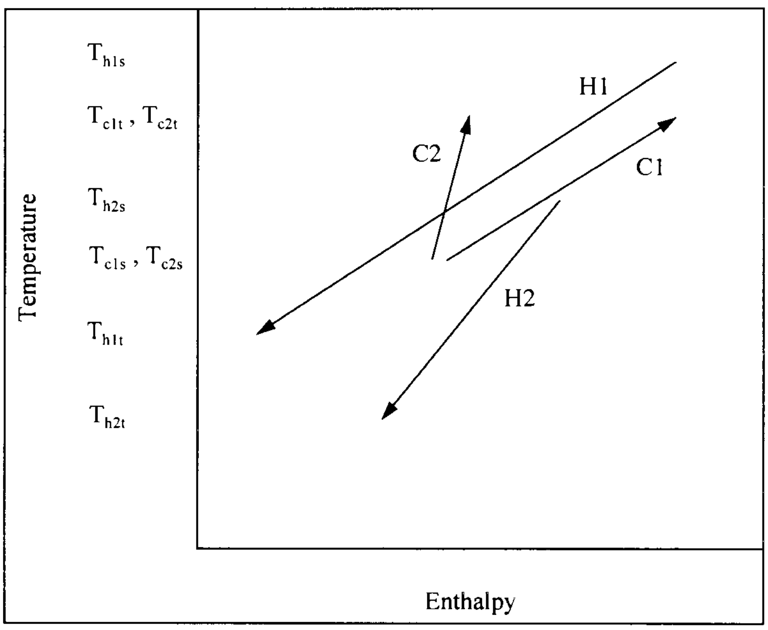

Figure 5.5b: Case in which C1 is the first cold stream to be matched

In Figure 5.5b the first cold process stream to be matched with hot process stream H1 is C1. Energy transfer from hot process stream H1 completely satisfies the energy requirement of cold stream C1. Once the choice of H1 and C1 is made, there is no process stream that can completely meet the energy requirement of cold process stream C2. This means that a hot utility has to be supplied in order for C2 to reach its target temperature.

When the process stream has been found, the next step is to select the hot process stream, as explained below.

b. Selection of the hot process stream

i. *Identify the hot process stream that has the lowest supply temperature and that can exchange energy with the cold process stream selected above.*

This step is a precautionary measure used to ensure minimum utility consumption, subject to match optimality. The cold process stream selected will be matched with several hot process streams in order to reduce its heat load as much as possible before a hot utility is used. The hot process stream identified in this step may be used to heat the coldest section of the cold process stream selected.

In Figure 5.5a the hot process stream that has the lowest supply temperature and that can also exchange energy with C2, the first cold process stream to be matched, is H2.

ii. *Identify the hot process stream that has the highest supply temperature*

This step is meant to identify the hot process stream that can supply energy to the hottest fragment of the cold process stream selected. It is to be realised that a process stream may have to exchange energy with a number of streams before its energy requirement is met. Steps b.i and b.ii above are adopted to make sure that energy received from the hot streams is used efficiently.

In Figure 5.5a the hot process stream that has the highest supply temperature is H1.

iii. *Identify the prospective match and evaluate its selection.*

In the column of the Selection Matrix that contains the cold process stream selected, add the heat loads of the feasible matches in a decreasing order of the supply temperature of the hot process stream until the sum is equal to or just greater than the heat load of the cold process stream. Identify the process match involving the last heat load added.

Two or more matches in this column may involve a hot process stream that has the same target temperature as that of the hot process stream in the match just identified. If this is the case then choose the match involving the hot process stream whose heat capacity flowrate is closest to that of the cold process stream. Evaluate the match chosen against the hot utility match involving the cold process stream as explained in the next paragraph.

Compare the match unit cost of the process match selected to that of the hot utility match involving the cold process stream in the process match selected. If the match unit cost of the process match is higher than that of the hot utility match, check if the annual capital cost of the process match is higher than the total annual cost of the utility match. If the annual capital cost of the process match is higher than the total annual cost of the utility match then place the utility match in the network. Otherwise place the process match in the network.

If the cold process stream to be matched is the last cold process stream the match evaluation step involves both hot and cold utilities. If the match unit cost of the process match is higher than that of the alternative utility match involving the cold process stream all possible utility matches yet to be placed in the network must be considered. The total cost of the process match and the utility matches associated with its choice must be compared to the total cost of the matches associated with the alternative utility cost.

The selection process is illustrated below, with reference to Figure 5.6.

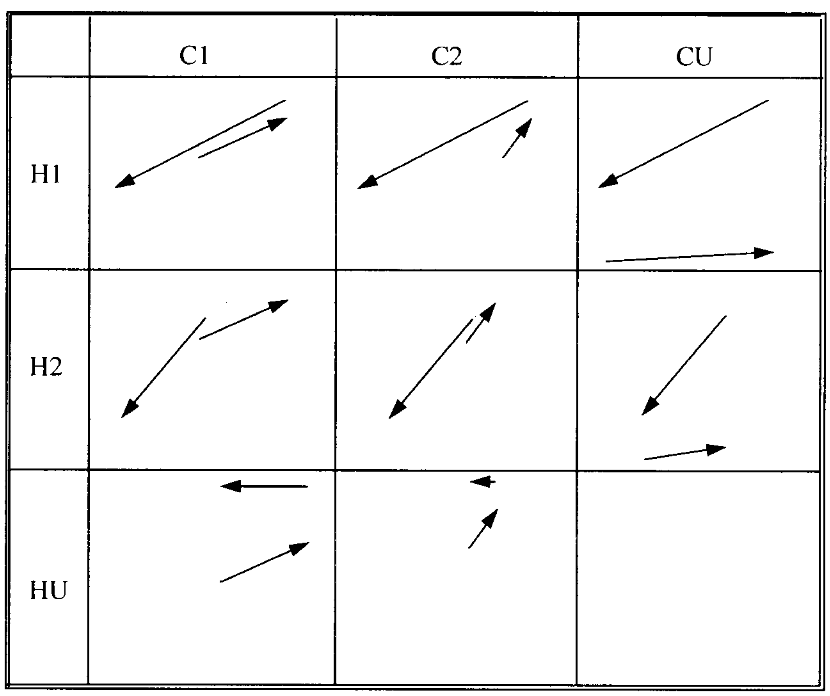

Figure 5.6: Sketch of the Selection Matrix used to illustrate match selection.

The cold process stream to be matched first, as selected above, is C2. There are a number of match options for C2. Possible matches are [H1,C2], [H2,C2], and [HU,C2]. It is desirable to choose the best option, an option that not only meets the energy requirement of C2 but that also takes into consideration the effect of the match on the remaining possible matches.

In Figure 5.6 the first match to be chosen is in column C2. In this column the hot process stream that has the highest supply temperature is H1. The heat load of [H1,C2] is compared to the heat load required to heat C2 from its supply to its target temperature. Since the heat load of match [H1,C2] is equal to the heat load of cold process stream C2, this match is evaluated against the utility match [HU,C2]. If the match unit cost of match [H1,C2] is less than or equal to that of utility match [HU,C2] then the match [H1,C2] is selected and placed in the network. On the other hand, if the match unit cost of [H1,C2] is greater than that of utility match [HU,C2] the annual capital cost of match [H1,C2] is compared to the total annual cost of utility match [HU,C2]. The match that has the smaller cost is then selected and placed in the network.

If match [H1,C2] is placed in the network, the residual of hot process match H1 can still satisfy the energy requirement of cold process stream C1, as shown in Figure 5.5a. Before match [H1,C1] is placed in the network, it is evaluated against the utility match [HU,C1]. Since this is the last cold process stream to be placed, the evaluation of [H1,C1] against [HU,C1] must also include consideration of [H1,CU]. That is, the sum of the annual costs of matches [H_{r2}1,C1] and [H1,CU] must be compared to the sum of the costs of matches [H_{r1}1,CU] and [HU,C1]. H_{r1}1 and H_{r2}1 are the first and second residuals of hot process stream H1.

Matches selected are placed in the network in a certain order. This is explained next.

5.1.5 Match sequencing procedure

1. Create the Selection Matrix.
2. Match each hot process stream with each cold utility, if this is feasible and allowable.
3. For each row of the Selection Matrix select the cold utility associated with the cold utility match that has the smallest match unit cost. The cold utility selected is the active utility

for the particular row or hot process stream and is used to optimise process matches in the row. It is also used to cool down the hot process stream if this is necessary.

4. Match each cold process stream with each hot utility, if this is feasible and allowable.

5. For each column of the Selection Matrix select the hot utility associated with the hot utility match that has the smallest match unit cost. The hot utility selected is the active utility for the particular column or cold process stream and is used to optimise process matches in the column. It is also used to heat the cold process stream if this is necessary.

6. Optimise each feasible, allowable process match.

7. Starting with preferred matches, if there are any, select and place a match in the network as explained in the match selection procedure in the preceding section. Follow the rest of the steps given below.

8. Update the row and column that meet at the position of the match just placed, by replacing each of the original process streams with its residual fragment in all the matches in the row or column. In the case of two residual stream fragments having been created from a parent process stream, create a new row or column between the last process stream and the first utility stream. Place the hotter process stream fragment in this new row or column and leave the colder fragment in the original row or column. It does not matter which of the two stream fragments goes to the new row or column; the aim is to separate the two stream fragments so that they represent two process streams. Each row or column involving a residual process stream is updated accordingly. Each match that involves a process stream whose target temperature has been reached becomes invalid.

9. For the match just placed, match any residual hot process stream with each cold utility. Match any residual cold process stream with each hot utility.

10. For both the row and the column associated with the match just placed identify the active utilities. There is no guarantee that active utilities remain the same in the case of multiple utility problems. Use the utilities identified to optimise all feasible and allowable process matches in the corresponding row or column.

11. Repeat steps 7 to 10 until all feasible and allowable matches have been placed in the network.

The algorithm will now be illustrated with an example, using the problem of Example 4.2 of Chapter 4. The stream and cost data after stream arrangement are shown in Table 5.1.

Example 5.2: Design of a preliminary network.

The stream data shown in Table 5.1 were derived from Figure 5.3, in which each of the cold process streams C1 and C2 was fractured into two fragments. Let the first and second stream fragments obtained from C1 be C1-1 and C1-2, and the two stream fragments obtained from C2 be C2-1 and C2-2.

Table 5.1: Stream and cost data for Example 5.2 (Yee and Grossmann, 1990).

Stream	T_s (K)	T_t (K)	F_{cp} (kWK^{-1})
H1	443	333	30
H2	423	303	15
C1-1	353	408	20
C1-2	293	353	20
C2-1	408	413	40
C2-2	353	408	40
HU	450	450	
CU	293	313	

Cost data

U = 0.8 ($kWm^{-2}K^{-1}$) for all matches except ones involving steam

U = 1.2 ($kWm^{-2}K^{-1}$) for matches involving steam

Annual cost = 1000 × $[\text{area}(m^2)]^{0.6}$ for all exchangers except heaters

Annual cost = 1200 × $[\text{area}(m^2)]^{0.6}$ for heaters

Unit cost of steam = 80 \$ kW^{-1} yr^{-1}

Unit cost of cold utility = 20 \$ kW^{-1} yr^{-1}

Design situation: No stream splitting

Match sequencing

As explained in the procedure, the feasible matches were evaluated and the appropriate matches were placed in the network. The sequence in which the matches were placed is shown in the preliminary network, Figure 5.7.

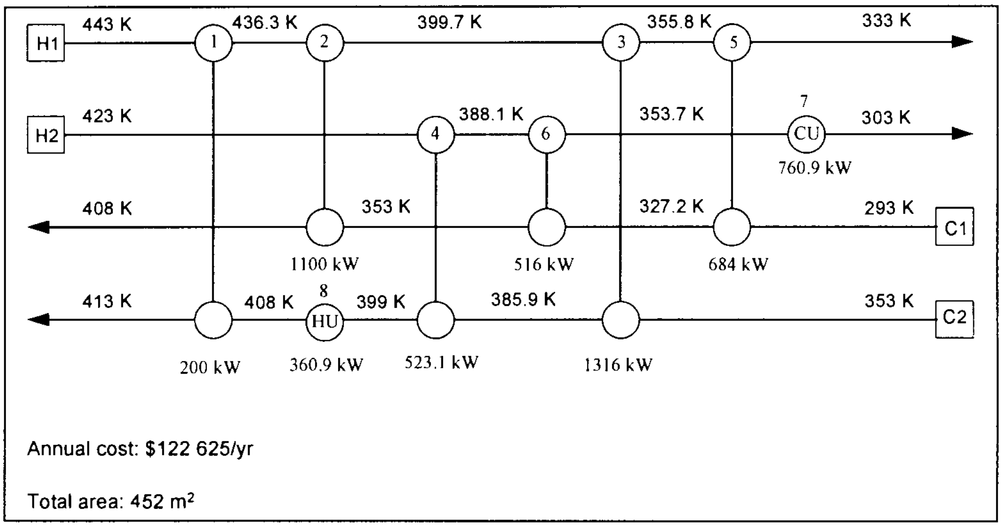

Figure 5.7: Preliminary network solution to Example 5.2.

A consequence of the stream arrangement process and the evaluation stage before match placement is the possible integration of utility matches with process matches. Utility matches can be placed in the network at any stage of the design process if this lowers the total network cost.

In Figure 5.7 cold process stream C1 was assembled from the fragments C1-1 and C1-2, while cold process stream C2 was assembled from fragments C2-1 and C2-2, created during stream arrangement. This is possible because the cold process streams were not physically fractured.

It will be noted in Figure 5.7 that the hot utility match has been positioned between process matches. The preliminary network is a cyclic structure, containing loops that can be manipulated to explore possibilities for the reduction of the network annual cost.

The preliminary network design obtained will now be examined for further improvement. This is done by evolutionary development discussed in the next section.

5.2 Evolutionary Development

Evolutionary development is a process whereby exchanger heat loads in a network are adjusted by re-distributing energy in order to achieve a lower network cost and to accommodate any possible specified temperature constraint.

Central to the process of evolutionary development are the concepts of a ***path*** and a ***loop***. A path is a sequence of units that are connected and has two distinct ends. A path has been defined by Linnhoff et al. (1982) as "a connection through streams and exchangers between hot utility and cold utility." In this project the utilities at the opposite ends of the path may be of the same type. That is, both utilities may be cold, or hot.

Lee and Reklaitis (1989) define a path as "an unbroken sequence of dependent units between any two independent ones, in which each pair of adjacent units has either a hot or a cold stream in common." According to these workers a unit is independent "if either its hot or its cold stream is only subject to a single contact or a match in the network."

A loop is a sequence of connected units such that the last unit is directly connected to the first one. Lee and Reklaitis (1989) define a loop as "a path, which connects an independent unit to itself."

The units that form a path or a loop in a network can be seen as elements of the path or loop. These elements of a path or loop may have full membership or partial membership. A process match is a full member if it shares both of its streams with one or two members of the path or loop. If a process match shares one stream with a member of the path or loop then it is a partial member of the path or loop. A partial member of a path or loop undergoes a change only in temperature if the heat loads of the full members change. If there is one utility match in a loop then the utility match can only be a partial member. For a utility match to be a full member of a path or loop the number of utility matches in the path or loop must be two.

Procedures for Evolutionary Development have been developed in the past (Boland and Linnhoff, 1979; Su and Motard, 1984). The procedure developed in this project differs in that instead of attempting to minimise the number of units, it attempts to minimise the network annual cost, with or without a reduction in the number of units. Minimisation of the number of units does not necessarily imply minimisation of the network annual cost. Furthermore, minimisation of the network annual cost does not necessarily imply minimisation of the number of units.

In the following section different types of paths and loops are described.

5.2.1 Types of Paths and Loops

Paths and loops may have different structures in terms of match type. A path will always have two utility matches, and may have process matches in addition to these utility matches. On the other hand, a loop may have two or more process matches. Each of these cases may involve partial membership of some process and/or utility matches. These different situations are illustrated in Figure 5.8a.

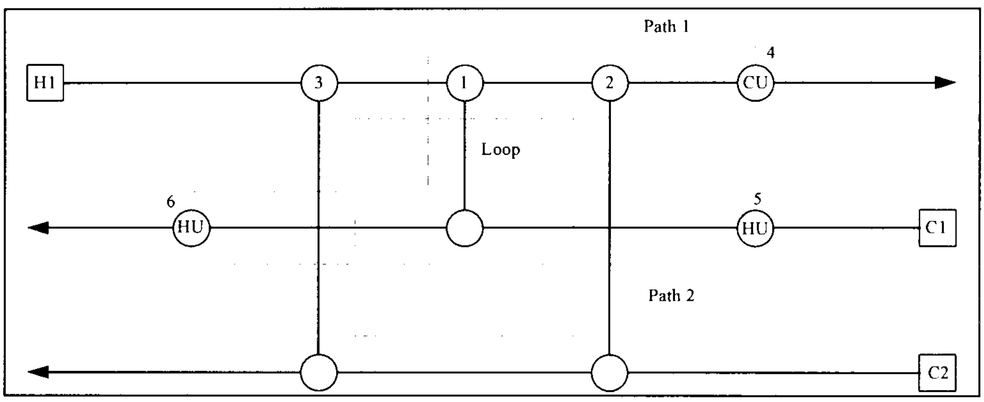

Figure 5.8a: A simple network showing two paths and one loop.

In Figure 5.8a there are two paths and one loop. The first path has three full members and one partial member. The full members are [HU,C1], [H1,C1], and [H1,CU]. The partial member in the path is [H1,C2].

Hot utility match [HU,C1] is a full member of the path because there is cold utility match [H1,CU] in the path, and vice versa. Process match [H1,C1] is a full member of the path because it shares hot process stream H1 with cold utility match [H1,CU], and shares cold process stream C1 with hot utility match [HU,C1]. Process match [H1,C2] is a partial member of the loop because it shares only one process stream with [H1,C1] and [H1,CU].

The second path has two full members and one partial member. The two full members are utility matches 5 and 6. The partial member is process match 1.

The loop shown in Figure 5.8a has two full members, matches 2 and 3. It has one partial member, match 1. All the members are process matches.

Paths and loops are not always as simple in structure as they are in Figure 5.8a. Paths and loops that are more complex are shown in Figure 5.8b.

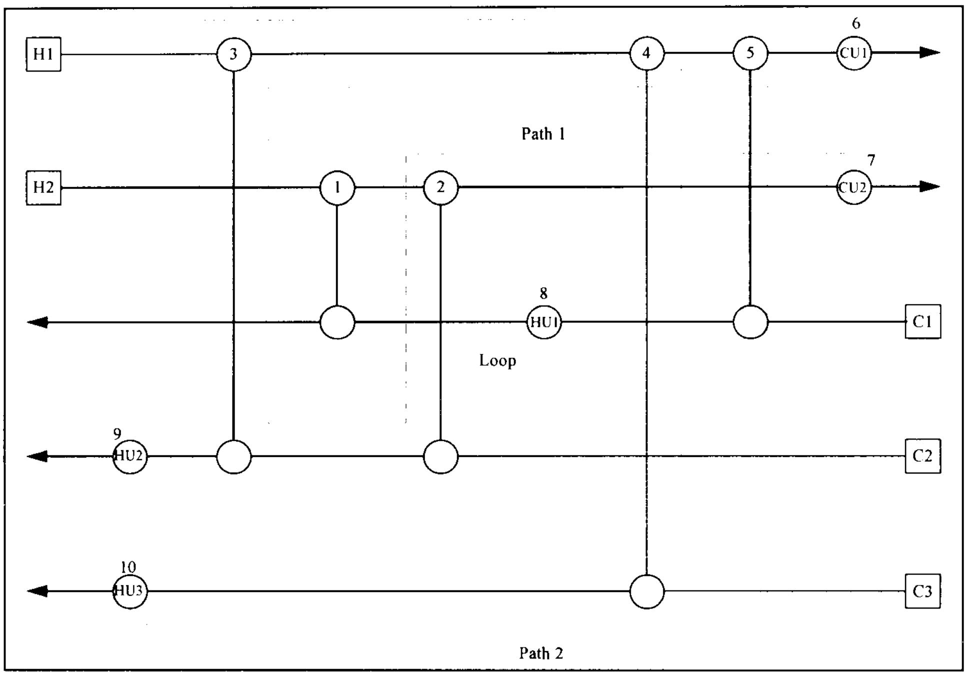

Figure 5.8b: A network showing one loop and different types of paths.

In Figure 5.8b there is only one loop. The loop has four full members and two partial members, and is [H1,C2]{H1,C3}[H1,C1]{HU,C1}[H2,C1][H2,C2][H1,C2]. Curly brackets have been used to indicate partial members {H1,C3} and {HU,C1}. Three types of paths can be identified in Figure 5.8b. The first type of path is that which involves two cold utility matches, such as [H1,CU1]{H1,C1}{H1,C3}[H1,C2][H2,C2][H2,CU2]. The second type of path involves two hot utility matches: [HU3,C3][H1,C3][H1,C2][HU2,C2]. The third type involves a hot utility and a cold utility: [HU3,C3][H1,C3]{H1,C1}[H1,CU1]

For small networks it is easy to identify paths and loops. This can be done by inspection. However, for large networks identification of paths and loops is difficult. It is therefore necessary to use a systematic approach to path and loop identification.

5.2.2 Identification of Paths and Loops in a Heat Exchanger Network.

The method for path and loop identification briefly described here is simple and effective. Su and Motard (1984) and Shenoy (1995) did more work on path and loop identification.

In order to identify paths and loops in a network a different schematic representation can be used. Circles can represent streams and lines can represent matches. A letter or letters and a number inside a circle identify the stream, and a number on a line identifies the match. This network representation is illustrated in Figure 5.9a.

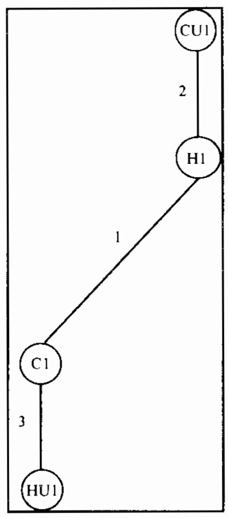

Figure 5.9a: Alternative representation of a network.

In Figure 5.9a match 1 is the process match [H1,C1]. Match 2 is the cold utility match [H1,CU1], and match 3 is the hot utility match [HU1,C1]. The digit 1 in HU1 means that the cold stream being heated is C1. The symbol CU1 can be interpreted in a similar manner.

In order to identify paths and loops, hot process streams are arranged in one row. Cold process streams are arranged in another row below the row of hot process streams.

A path is identified by tracing a route from a utility match to another utility match without repeating matches between these utility matches. A loop is identified by tracing a route from one process match back to the same starting match, without repeating matches in this route. The simple network in Figure 5.8a can be represented by Figure 5.9b.

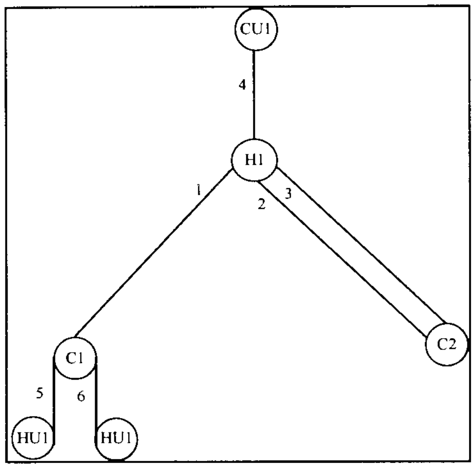

Figure 5.9b: Alternative network representation for Figure 5.8a.

In Figure 5.9b moving from H1 via match 2 to C2, and back from C2 can trace the only loop in the network via match 3 to H1. There are three paths: matches 5,1,and 4; matches 6, 1, and 4; and matches 5 and 6.

The loop shown in Figure 5.9b is simple since it involves only two process matches. Complex loops involve more than just two process matches. This situation is illustrated in the network equivalent of Figure 5.8b shown in Figure 5.9c.

Because of the arrangement of process streams in two rows, loops that have more than two process matches will have two lines that intersect each other. Points of intersection, such as A, B, and C in Figure 5.9c indicate loop possibilities. Since these points of intersection are easily identifiable, loops can be easily located.

By starting at one end of any of the lines that intersect, a loop can be identified by tracing a route which alternately connects a hot process stream and a cold process stream, until the starting point is reached. No process match should be visited more than once. A journey that does not end at the starting point indicates that the sub-structure tested is not a loop.

In Figure 5.9c a journey that starts at H1 can include matches 3, 2, 1, and 5. Match 5 completes the loop for point A. For each of points A, B, and C a loop search involves a journey through the point. Points B and C are not parts of any loop since no path can be traced from the starting point and back to the same point.

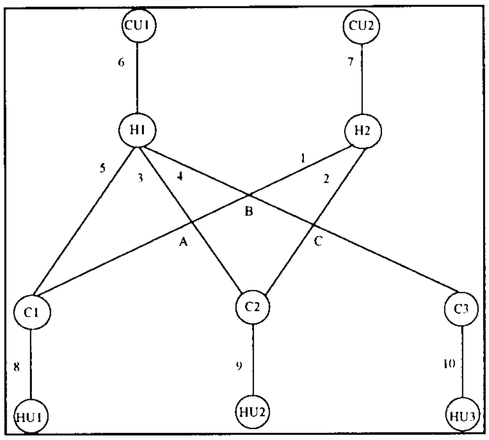

Figure 5.9c: Alternative network representation for Figure 5.8b.

The significance of paths and loops is that they can be optimised. There is a cost associated with each path or loop. This cost is a monotonic function of energy distribution along the path or around the loop. Since paths and loops are parts of the whole network, re-distribution of energy affects the total cost of the network. The variation of the path or loop cost with energy distribution is discussed in the next section.

5.2.3 Path and Loop Optimisation

In this section path optimisation and loop optimisation are described. A possible preliminary network for Example 4.1 (Table 4.2) of Chapter 4, shown in Figure 5.10, is used to illustrate path and loop optimisation. It can be seen that the network has one path and one loop. The objective of this section is to show how each of the path cost, the loop cost, and the network cost varies with energy distribution. The path or loop cost is the total annual cost of all the units (partial and full members) in the path or loop.

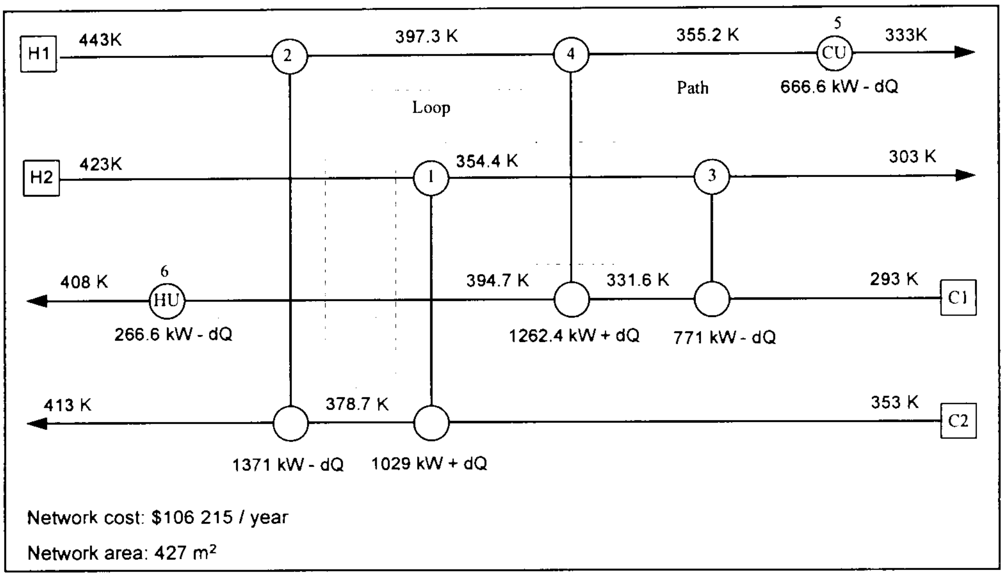

Figure 5.10: Preliminary network showing a path and a loop.

Path optimisation involves the removal of an energy increment dQ from the units in odd positions in the path and addition of this amount of energy to the units in even positions in the path, starting from one end and stopping at the other end of the chain. Both positive and negative energy increments are used because the direction of energy flow that minimises the total annual cost is not obvious.

The amount of energy dQ must be the same for each once-through pass in order to maintain the energy balance along the path. A once-through pass is one cycle, from the first unit in the path to the last one. The energy amount dQ may be varied from one pass to another.

For each exchanger whose heat load has changed because of this energy shift, the pertinent variables are updated. The pertinent variables are exchanger inlet and outlet temperatures, heat loads, and the total cost of the network. The process is repeated until either a thermodynamic constraint is violated or one of the heat loads in the path becomes zero. The aim behind this exercise is to choose exchanger heat loads that correspond to the lowest total annual cost possible.

The concept of path optimisation will now be illustrated with reference to Figure 5.10.

Example 5.3: Path optimisation.

The path that was identified in Figure 5.10 starts from heater HU, passes through process exchanger [H1,C1], and ends at the cooler CU. The original annual cost of this network was found to be $106 215/year. The minimum hot utility requirement for this problem was 0 kW and the minimum cold utility requirement was 400 kW.

In Figure 5.10 an arbitrary energy increment dQ is removed from heater HU. This amount of energy is added to process exchanger [H1,C1], because its position is even, namely 2, starting from the heater HU. Since cooler CU is the third unit from HU, the energy increment is removed from it. The variation of the heat load, path cost, and the network cost with energy increment is shown in Table 5.2a.

Table 5.2a: Variation of heat load and annual cost with energy distribution along the path in the network shown in Figure 5.10.

Energy increment, kW	Exchanger heat load, kW			Annual cost, $/year	
	[HU,C1]	[H1,C1]	[H2,CU]	Path	Network
-1262.4	1529	0	1929	176 759	217 847
-1200	1467	62	1867	171 446	212 535
-1100	1367	162	1767	162 064	203 152
-1000	1267	262	1667	152 523	193 612
-900	1167	362	1567	142 932	184 021
-800	1067	462	1467	133 333	174 422
-700	967	562	1367	123 755	164 843
-600	867	662	1267	114 226	155 315
-500	767	762	1167	104 783	145 872
-400	667	862	1067	95 481	136 570
-300	567	962	967	86 413	127 502
-200	467	1 062	867	77 764	118 852
-100	367	1 162	767	70 002	111 090
0	**266.6**	**1262.4**	**666.6**	**65 127**	**106 215**
50	217	1312	617	73 798	114 886

The table shows that when an energy increment of 1262.4 kW was re-distributed along the path the only process exchanger in the path, [H1,C1], was eliminated. Under these conditions the path was broken. The number of units in the network decreased from six to five. The minimum number of units for this problem is four. Although the number of units decreased, the network cost did not decrease, instead it increased from the original value of \$106 215/year to \$217 847/year. This increase in the network annual cost was caused by the increase in utility consumption to 1929 kW of cold utilities and 1529 kW of hot utilities. This utility consumption far exceeds the minimum requirement of only 400 kW of the cold utility. The minimum annual cost of the network occurred when the energy increment was zero. This suggests that the preliminary network cannot be improved further by re-distributing energy along the path.

None of the utility matches could be eliminated. In a path, only the unit that has the smallest heat load in the odd position, or the unit that has the smallest heat load in the even position, can be eliminated. Thus, only the heater (266.6 kW), rather than the cooler (666.6 kW) can be considered for elimination in the path of Figure 5.10. However, for the network configuration or topology shown in the figure, the amount of energy that can be removed from the heater is constrained by the inlet temperature of match 4, [H1,C1]. Only a maximum amount of 52.6 kW can be removed from the heater. When this is done the outlet temperature of the cold process stream in match 4 becomes equal to the inlet temperature of the hot process stream in this exchanger. Hence, the heater cannot be removed from the network. Removal of energy of up to 52.6 kW from the heater results in an increase in the network annual cost. This suggests that the path in the original network is at its optimum condition.

The variation of the path annual cost and the network annual cost with energy distribution is shown in Figure 5.11a. Both costs show a similar behaviour pattern. It can be seen that energy distribution in a path affects the network annual cost. It must be pointed out that the optimum distribution of energy along a path does not necessarily imply an optimum network cost. One reason for this is that there could be other paths or loops in the network that are not optimal. Another reason why an optimum energy distribution along a path may not imply an optimum network cost is that the network examined may be just one of a number of possible basic structures or topologies.

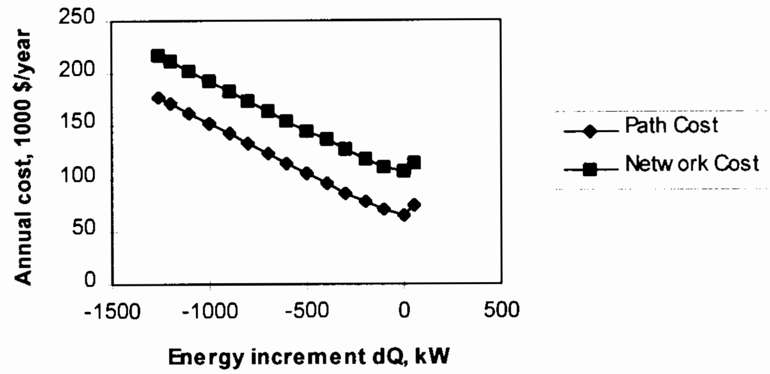

Figure 5.11a: Variation of the path cost and the network cost with energy distribution along the path.

Since there is also a loop in the network shown in Figure 5.10, it would be worthwhile to optimise the loop in an effort to reduce the network annual cost. This is done in Example 5.4.

Example 5.4: Loop optimisation.

Loop optimisation in Figure 5.10 was performed by removing an amount of energy dQ from match 2, adding it to match 4, removing it from match 3, and adding it to match 1. The results are shown in Table 5.2b.

Temperature constraints in the network were such that the loop could not be broken. These constraints can be described with reference to match 2. The energy increment that can be added to match 2 is constrained by the exchanger inlet temperature of the hot process stream into match 4.

The amount of energy that can be removed from match 2 cannot be equal to or greater than 79 kW, because at this value match 4 becomes thermodynamically infeasible. The hot-end temperature difference of match 4 becomes negative.

The amount of energy that can be removed from match 2 is constrained by the outlet temperature of the hot process stream in match 1. When the amount of energy removed from match 2 increases to 21 kW, the cold-end temperature difference of match 1 becomes zero. When dQ is larger than 21 kW the cold-end temperature difference of match 1 becomes negative.

Table 5.2b shows that the lowest annual cost is achieved when dQ is -10 kW. The network annual cost was reduced only slightly (0.3%) by loop optimisation for this particular network configuration or topology.

Table 5.2b: Variation of heat load and annual cost with energy distribution around the loop in the network shown in Figure 5.10.

dQ, kW	Exchanger heat load, kW				Annual cost, $/year	
	[H1,C2]	[H1,C1]	[H2,C1]	[H2,C2]	Loop	Network
-70	1441	1192.4	841	959	69 229	112 968
-60	1431	1202.4	831	969	66 078	109 817
-50	1421	1212.4	821	979	64 378	108 117
-40	1411	1222.4	811	989	63 305	107 044
-30	1401	1232.4	801	999	62 621	106 360
-20	1391	1242.4	791	1009	62 243	105 982
-10	1381	1252.4	781	1019	62 167	105 906
0	1371	1262.4	771	1029	62 476	106 215
10	1361	1272.4	761	1039	63 501	107 240
20	1351	1282.4	751	1049	68 548	112 287

The variation of the loop cost and the network cost with energy distribution is shown in Figure 5.11b. The effect of loop optimisation on the network cost is evident. The two cost curves have their minima at the same value of the energy increment.

Since the utility matches are not members of the loop they remain unaffected by loop optimisation. Although loop optimisation reduced the network cost slightly, the amount of utilities (266.6 kW of hot utility and 666.6 kW of cold utility) remain much higher than the minimum requirement of 400 kW of cold utilities. This suggests that the network after loop optimisation was performed may not be optimal.

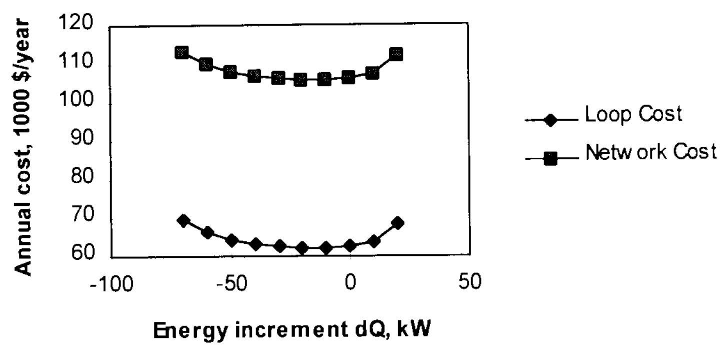

Figure 5.11b: Variation of the loop cost and the network cost with energy.

Any further attempt to reduce the network cost would probably involve a structural change in the basic preliminary network. This may involve re-arrangement of the positions of some of the units in the network.

5.2.4 Structural Optimisation

Optimisation of paths and loops may not be sufficient to ensure network optimality. Sometimes it is necessary to change the positions of the matches in order to reduce the network annual cost. This is a mechanism for moving from one basic network structure to another.

The positions of individual matches with respect to one another in a network may affect network optimality significantly. In other words, there is an optimum position for each match in a network. It is therefore necessary to check if the matches are in their optimum positions.

The concept of path or loop optimisation can be used not only to eliminate matches but also to create new matches during evolutionary development. This is achieved by transferring energy from existing matches to possible match sites. Possible match sites must be connected to existing matches by paths or loops before they can be modified into actual matches.

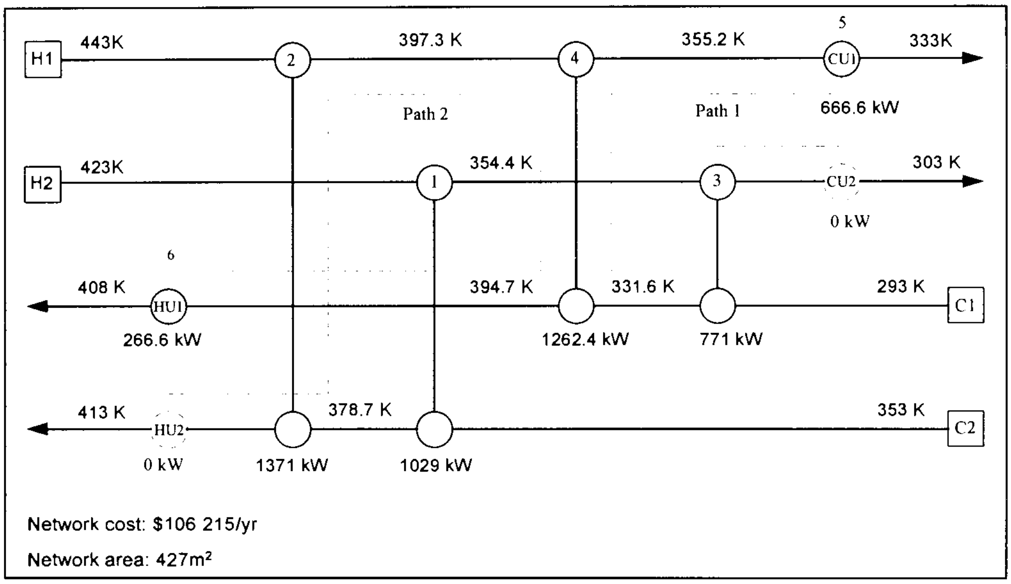

Figure 5.12: Network showing alternative positions for utilities.

As can be seen in Figure 5.11, the cooler can be moved to a new position on hot process stream H2. A path to the existing cooler connects the new match site. Energy can be transferred from the existing cooler to the new match site. The behaviour of the network annual cost during this process is shown in Figure 5.12a.

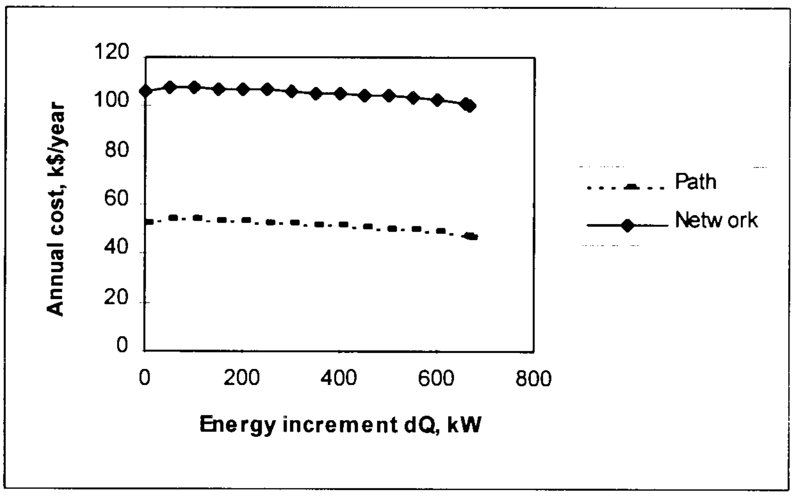

Figure 5.13a: Change in the annual cost as the cooler is moved from stream H1 to H2 in Figure 5.12.

When all the energy is moved from cooler CU1 to cooler CU2 the network annual cost is reduced by 5.5%. Therefore the cooler should be placed on stream H2 rather than on stream H1.

The variation of the annual cost with energy removed from the heater to a new match site is shown in Figure 5.13b.

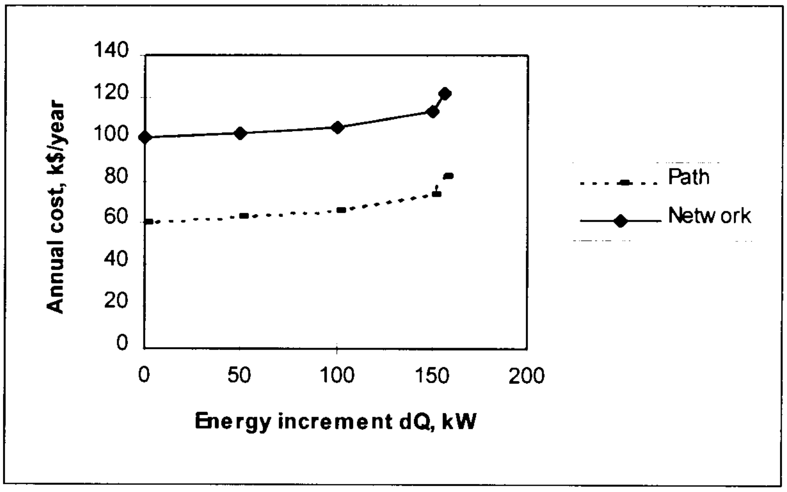

Figure 5.13b: Variation of the annual cost with energy removed from heater HU1 to heater HU2 in Figure 5.12.

The amount of energy that can be removed from heater HU1 to HU2 in Figure 5.12 is constrained by the hot-end temperature difference of match 4. Only a maximum of 157 kW can be removed from HU1 to HU2. When this is done, the network cost of $100 348/year reached by moving the cooler from H1 to H2 is increased by 21.5%. Therefore the heater should remain in its original position as HU1.

Appropriate positions for the process exchangers can be determined in a similar manner. The new process exchanger must complete a loop with existing units.

When a new unit is created, the change in the network annual cost is determined by the relative conditions (temperature driving forces and heat loads) at the old and new positions, as well as by the interactions of the other units in the path or loop. A change in the condition of one member of a path or loop propagates along the path or around the loop.

In this section it has been observed that path optimisation, loop optimisation, and structural optimisation affect network optimality. In the following section a brief discussion of network cost reduction is given.

5.2.5 Network Cost Reduction

The concepts of path optimisation, loop optimisation, and structural optimisation can be used to reduce the cost of a preliminary network. The major steps taken to reduce the network cost are given below.

1. *Identify all the paths and loops in the network*

The objective of this step is to keep track of the paths and loops already optimised and those yet to be optimised.

2. *Optimise paths and loops*

While the paths and loops are optimised, the network cost is monitored. Each optimisation should lead to a reduction in the network annual cost. It is not always obvious which path or loop should be optimised first. Sometimes different paths or loops share units and are thus dependent on each other. It may be necessary to optimise a path or loop more than once, at different stages of the evolutionary development.

If the path or loop optimisation does not result in a network cost reduction its condition just before optimisation is kept unchanged. Although it is desirable to first optimise paths and loops that involve the most expensive matches, this may not always be possible. However, the idea is to reduce the cost of the most expensive matches, but this may be achieved by increasing the costs of cheaper matches. The process should, nevertheless lead to an overall cost reduction. The match unit cost gives an indication of the cost of each match.

The process of path optimisation and loop optimisation is continued so long as there are loops whose optimisation leads to a network cost reduction. This is an iterative process.

3. ***Perform structural optimisation***

This step is intended to ensure an optimum position for each unit in the network. It involves a gradual removal of energy from a unit to an alternative match site. The network annual cost is monitored in the process. If removal of part or the whole of the energy of the unit in question results in a network cost reduction, the network is kept at that state of lower cost. The rest of the matches are examined. This process may lead to a reversal of the order of some matches in the network, or the creation of new matches while the parent matches remain with a smaller heat load.

Because of the complexity of the interactions between matches in a network no single order of steps is known that will reduce the network cost quickly. Only possible guidelines can be suggested for the removal of an existing unit to a new match site. A possible guideline is to move the most expensive matches to positions that involve:

- A higher temperature driving force; and/or
- A higher overall heat transfer coefficient.

Steps 1 to 3 may have to be performed a number of times before a satisfactory cost reduction is achieved. After elimination or creation of a unit it may be necessary to identify all the paths and loops present at that stage. There may be no single order that is applicable to all design cases. The best approach at the moment is to explore all cost reduction possibilities until the network annual cost is within a satisfactory range from the target or cost limit.

For each stream it is possible to check the effect on network annual cost of reversing the positions of any two matches. There are three possible outcomes when the positions of two matches are reversed:

1. The operation may be thermodynamically invalid;
2. The optimum annual cost may decrease; or
3. The optimum annual cost may increase.

The process of network cost reduction will now be illustrated with the preliminary network obtained in Example 5.2, Figure 5.7.

Example 5.5: Evolutionary development of the preliminary network obtained in Example 5.2.

The sketch used to identify paths and loops in the network is shown in Figure 5.14. This sketch is compared with Figure 5.7 in order to include partial members of the paths and loops. Five paths and six loops were identified, and are shown in Table 5.3.

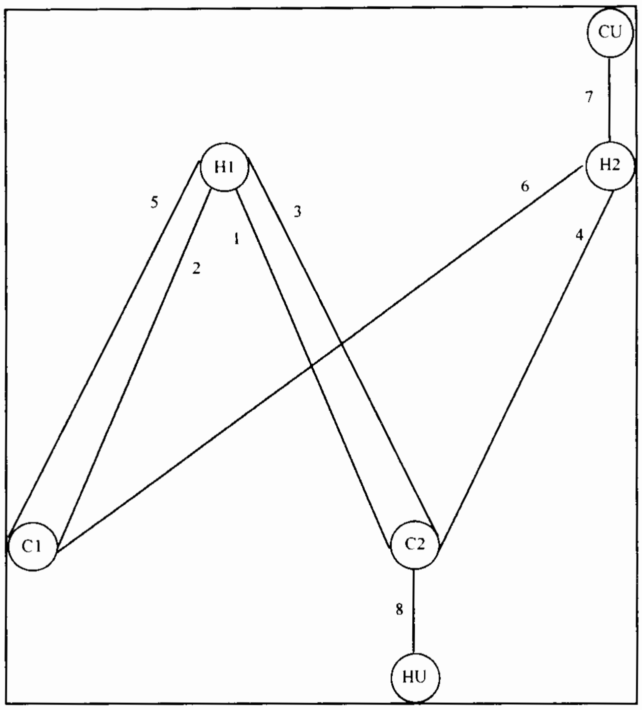

Figure 5.14: Sketch used to identify paths and loops in the network shown in Figure 5.7.

Table 5.3: Paths and loops identified in the preliminary network obtained in Example 5.2.

Path	Matches	Loop	Matches
1	7, 6, 4,8	1	1, 2, 3, 4, 8
2	7, 6, 2, 1, 8	2	2, 3, 5, 6
3	7, 6, 2, 3, 4, 8	3	1, 2, 6, 4, 8
4	7, 6, 5, 3, 2, 1, 8	4	1, 2, 3, 5, 6, 4, 8
5	7, 6, 5, 3, 4,8	5	2, 3, 4, 6
		6	5, 3, 4, 6

In Table 5.3 partial members in the path or loop are underlined. Loops 1 and 2 in the table are simple, each having only two matches that are full members of the loop. In order to simplify the network, simple loops are optimised first. This decision may lead to a smaller number of paths and loops if some of the matches are eliminated. The cost reduction stages are discussed below.

Path and Loop Optimisation

In order to monitor progress in the network cost reduction the optimisation of a path or loop will be called a development stage.

Stage 1

The original preliminary network, showing the first loops to be optimised, is shown in Figure 5.15a.

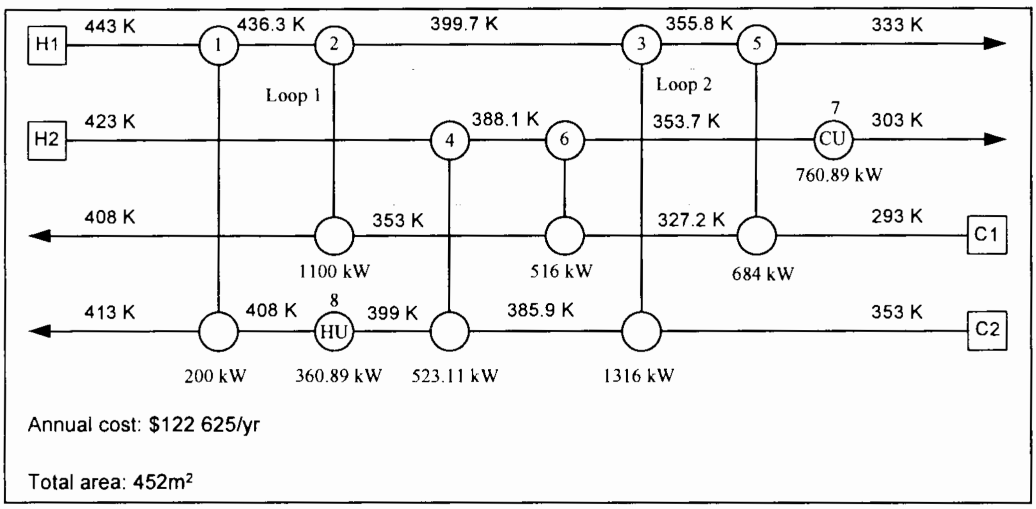

Figure 5.15a: Preliminary network showing the first two loops to be optimised.

Optimisation of Loop 1 did not result in elimination of a unit from the loop. The annual cost of the network was reduced only slightly, by 1.7%, from $122 625/year to $120 521/year.

The variation of the network annual cost with energy distribution around Loop 1 is shown as Stage 1 in Figure 5.16. In order to reach loop optimality energy (288 kW) was removed from match 3 to match 1. The next stage should therefore reduce the network annual cost from $120 521/year to a lower value. Loop 2 was next to be optimised.

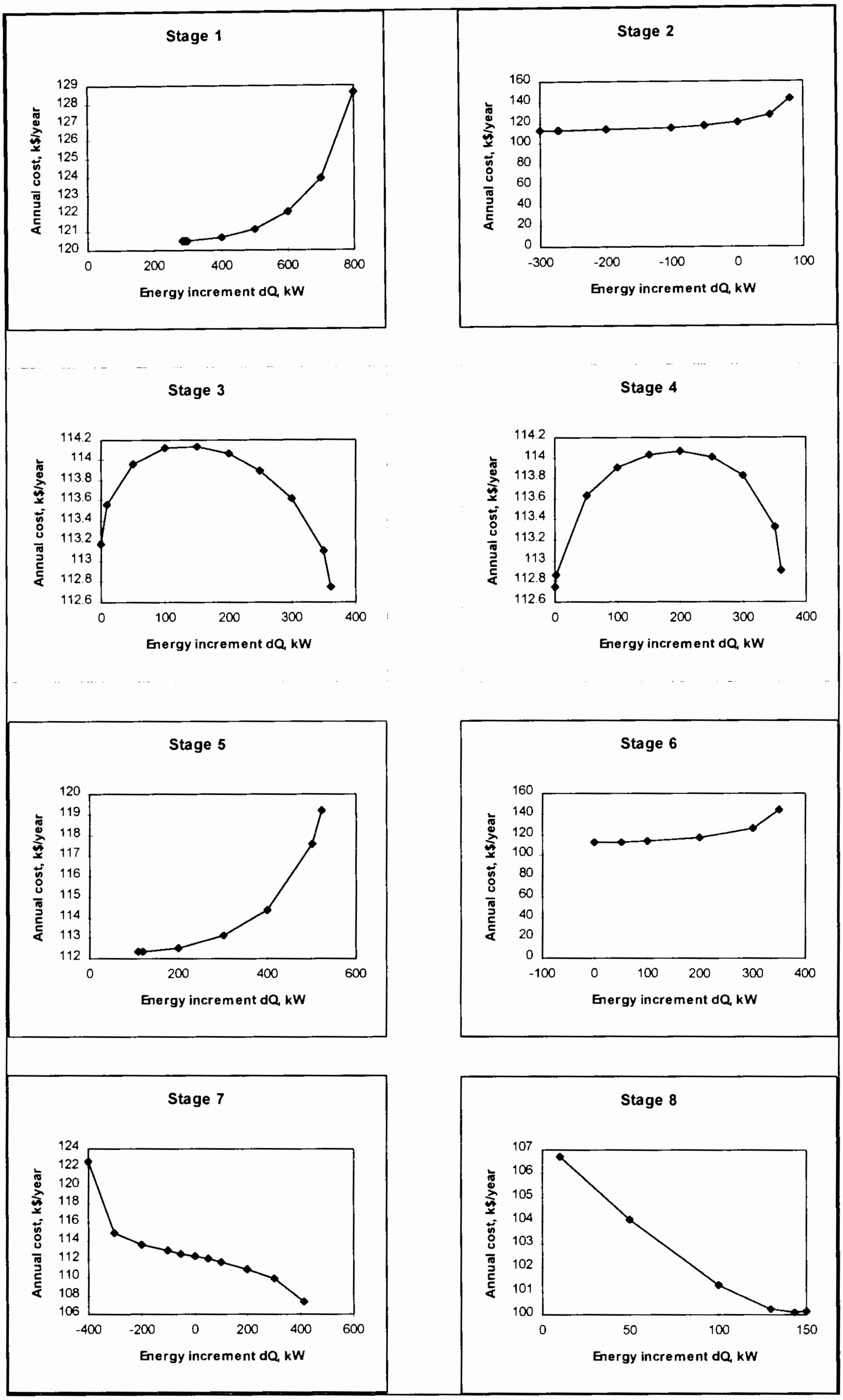

Figure 5.16: Variation of the network annual cost with energy distribution during each stage of optimisation.

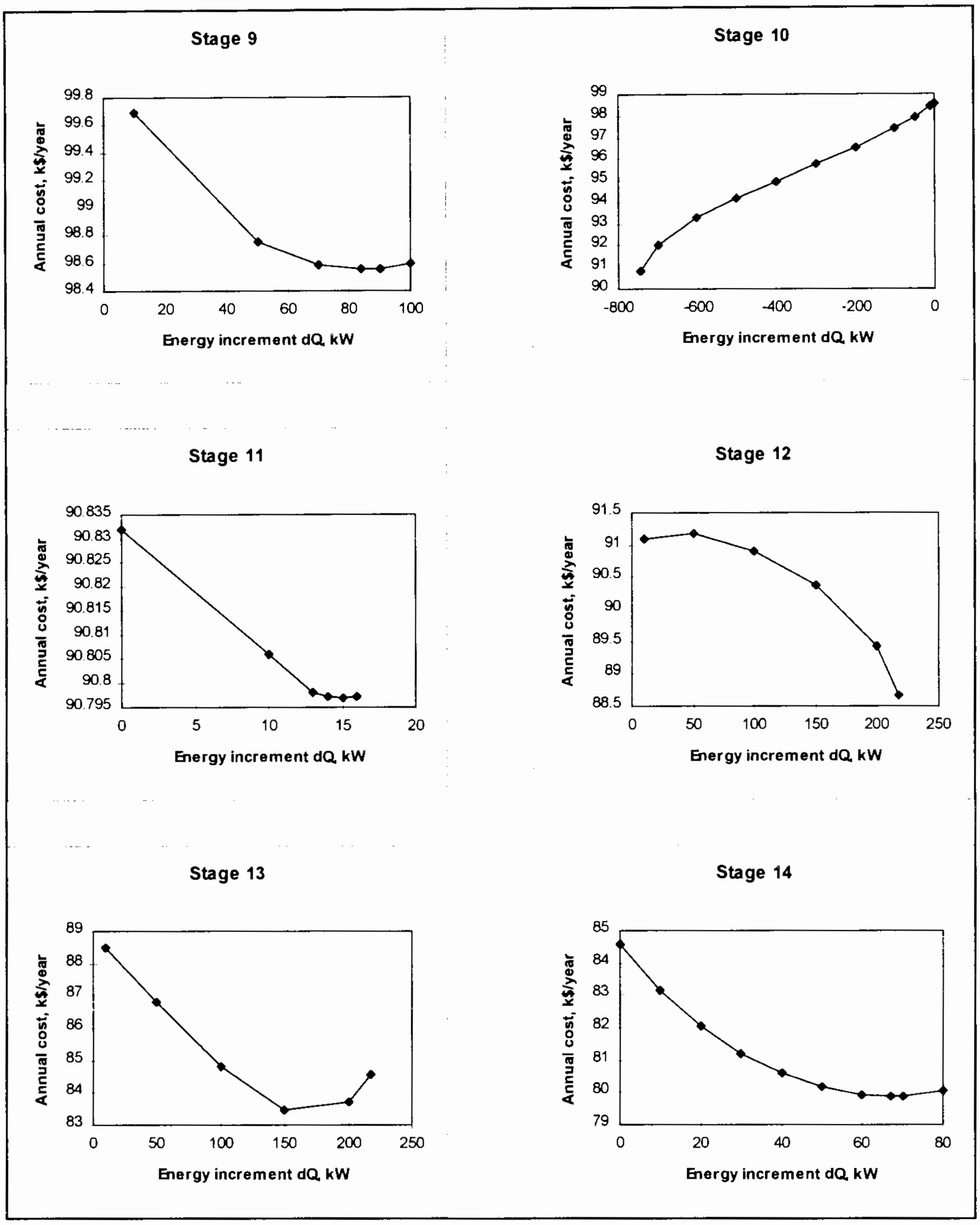

Figure 5.16 (continued): Variation of the network annual cost with energy distribution during each stage of optimisation.

Stage 2

The second loop was also not broken during optimisation. The network annual cost was reduced by 7.7% from $120 521/year to $113 166/year. The optimum point was achieved by shifting 272 kW from match 2 to match 5. The variation of the network annual cost with energy distribution is shown as Stage 2 in Figure 5.16.

Stage 3

The next step involved the heater. Its alternative position is shown in Figure 5.15b.

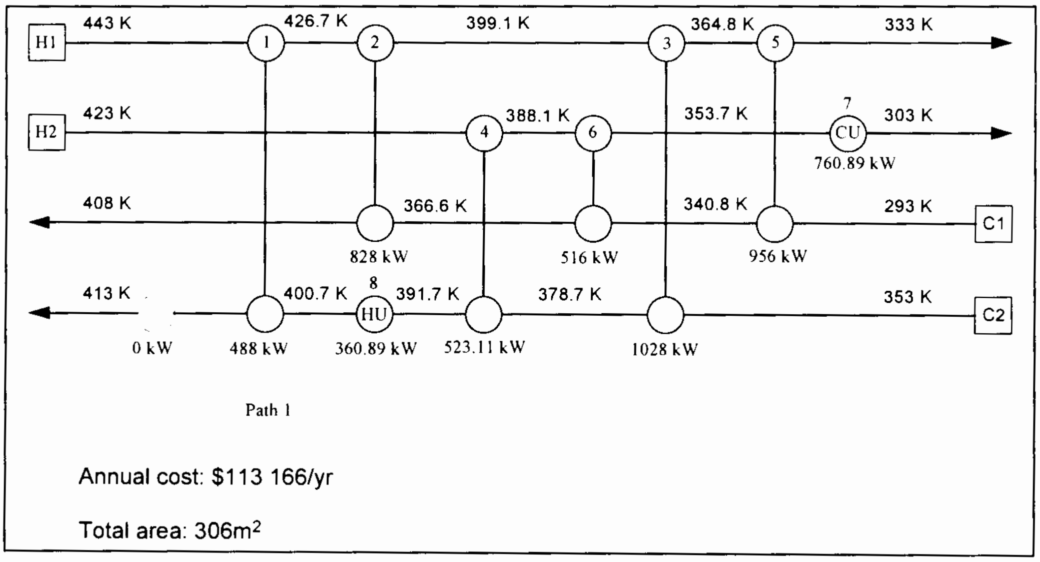

Figure 5.15b: Network structure at the beginning of Stage 3.

When the heater was moved along Path 1 from its original position to the hottest end of cold process stream C2 the network annual cost decreased very slightly (0.4%) from the latest network annual cost of $113 166/year to $112 748/year. The cost reduction process is illustrated in Stage 3 of Figure 5.16.

Stage 4

This step was an attempt to move the heater from the hottest end of cold process stream C2 to the hottest end of cold process stream C1. This was done because the target temperature of stream C1 is lower than that of C2. Thus, the heater at the new position would have a smaller heat transfer surface area because of the higher temperature driving force. However, the path (Path 2 involving matches 1, 2, and 8, and the new match site) used to shift energy from the original heater position to the new heater site did not favour cost reduction. The network annual cost increased from $112 748/year to $112 909/year. The heater was therefore not moved to cold process stream C1.

The variation of the network annual cost with energy distribution along the path is shown in Figure 5.16.

Stage 5

This step involved optimisation of Loop 3, shown in Figure 5.15c.

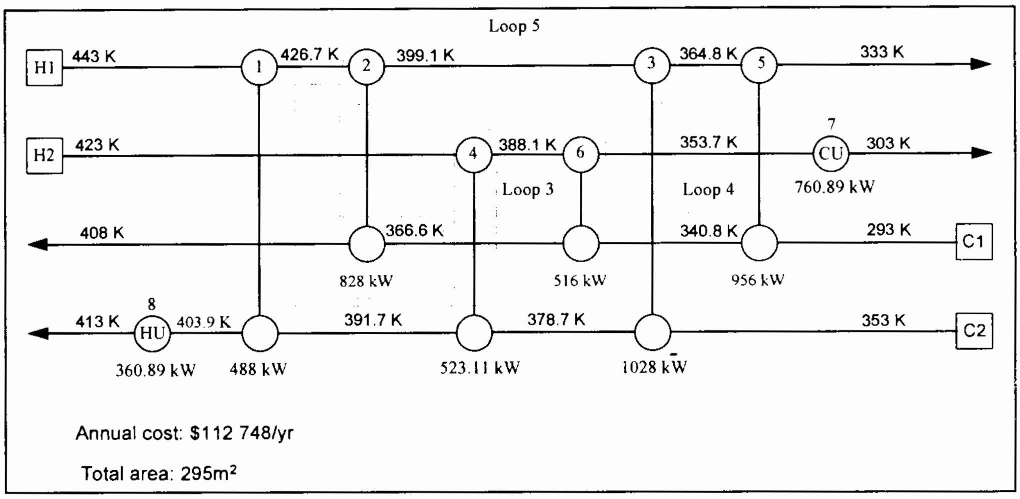

Figure 5.15c: Structure of network before optimisation of Loops 3, 4, and 5.

The loop shown in Figure 5.15c was not broken during the optimisation process. The optimum annual cost of the loop was reached after 110 kW of energy was removed from match 2 and distributed around Loop 3.

The value of the smallest heat load in the loop was 488 kW. As shown in Figure 5.16, Stage 5, the network annual cost increased with the amount of energy removed from match 2. Hence, removal of a match was not economically justifiable. The annual cost of the network after optimisation of Loop 3 decreased by 0.4% to $112 335/year.

Stage 6

Optimisation of Loop 4 in Figure 5.15c did not result in any reduction of the network cost. In other words, Loop 4 was already at its optimum condition. Any disturbance of this condition resulted in an increase in the network annual cost, as shown in Figure 5.16, Stage 6.

Stage 7

When Loop 5 in Figure 5.15c was optimised match 4 was eliminated. As shown in Figure 5.16, Stage 7, the network annual cost was lowest when the entire heat load of match 4 was removed from this match. The resulting network annual cost was $107 434/year. This network annual cost represents a reduction of 4.4% from the previous network annual cost.

Stage 8

The network obtained from Stage 7 is shown in Figure 5.15d. Path 3 in this network was optimised.

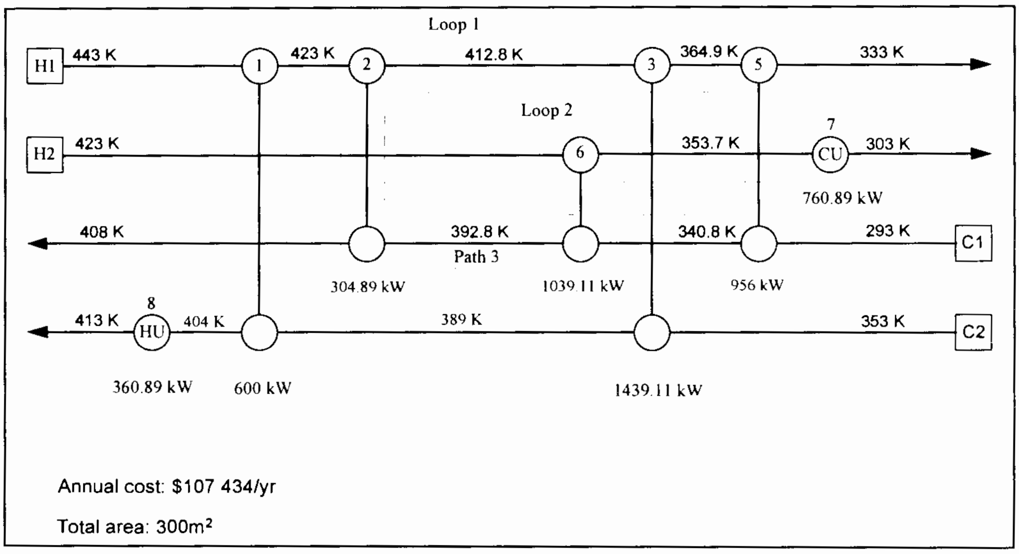

Figure 5.15d: Network structure before optimisation of Path 3.

After optimisation of Path 3 the network annual cost was reduced by 6.8% to $100 106/year.

Stage 9

In order to simplify the network structure, a second attempt was made to combine matches 2 and 5 in Figure 5.15d. These two matches form Loop 2. Optimisation of this loop resulted in a cost reduction of 1.5%, from $100 106/year to $98 554/year. The loop was not broken.

Stage 10

Another attempt was made to break Loop 1, now in Figure 5.15d. The optimum point was attained by eliminating match 1. The number of units in the network was therefore reduced by one, from seven to six. The network annual cost was reduced by 7.8% from $98 554/year to $90 832/year.

Stage 11

A third attempt was made to break Loop 2, in Figure 5.15d. The reduction in the network annual cost was insignificant, 0.04%.

Stage 12

After Stage 11 of the optimisation process the network structure was as shown in Figure 5.15e.

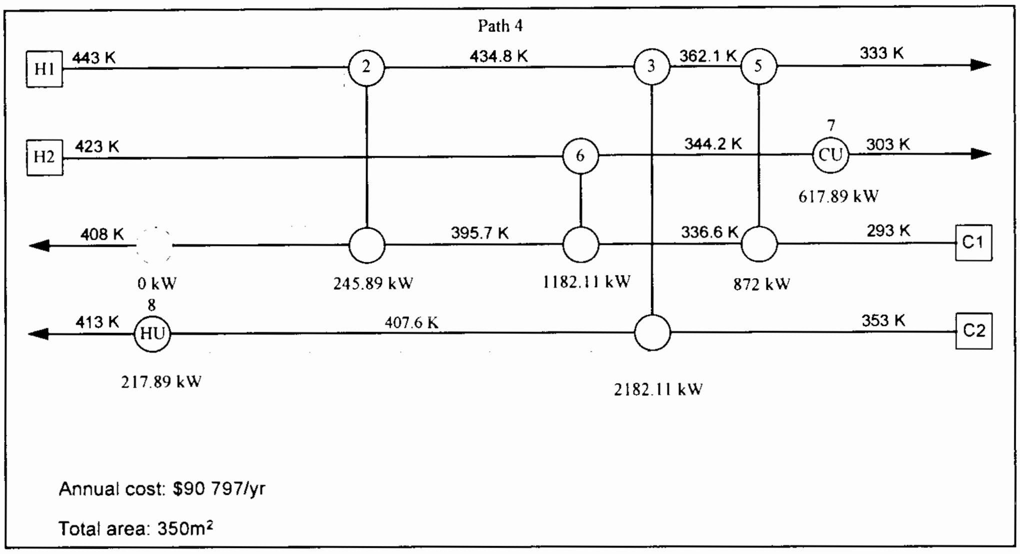

Figure 5.15e: Network structure before optimisation of Path 4.

Optimisation of Path 4 led to the removal of the heater from cold process stream C2 to C1. The network annual cost was reduced by 2.4% to $88 659/year.

It is to be noted that the minimum utility requirement is 400 kW of the cold utility. Since the load of the hot utility is about 218 kW this means that an extra amount of 218 kW will also be consumed. It is therefore important to try and eliminate the heater altogether.

Stage 13

The only way to eliminate the heater is to find a path that connects it to the cooler. Two possible paths that already exist are shown in Figure 5.15f as Path a and Path b.

However, use of either of these two paths requires that energy be added to match 6. The maximum amount of energy that can be added to match 6 is 124.39 kW. Since the heater has a heat load of 217.89 kW, it cannot be eliminated by optimisation of either Path a or b.

Creating a new process match therefore developed a new path. The new match is shown dotted, as match 9, and the new path is Path 5. Match 9 received its heat load from the heater.

The replacement of the heater by process match 9 resulted in a cost reduction of 4.6%, from $88 659/year to $84 566/year.

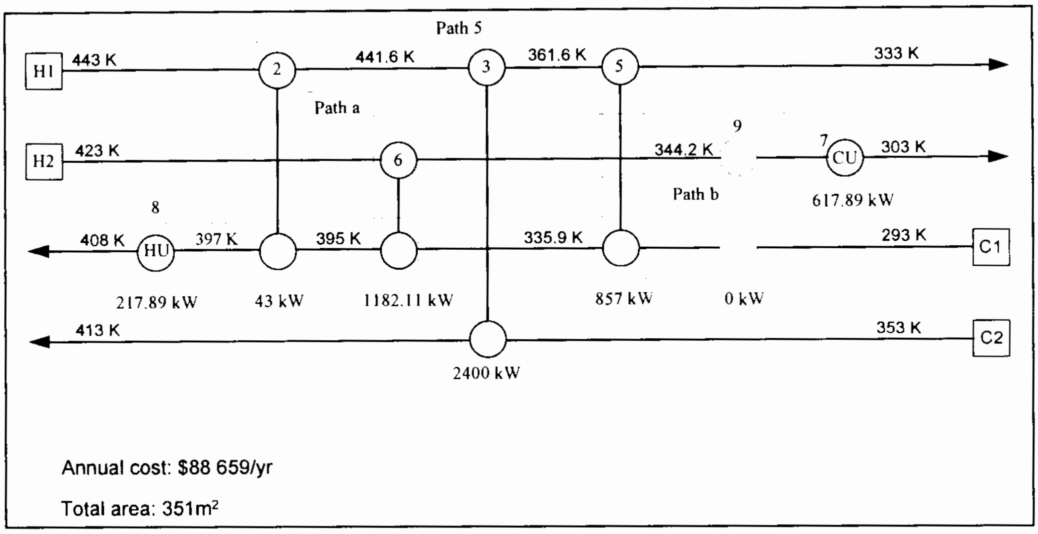

Figure 5.15f: Network structure before elimination of the heater.

Stage 14

When the heater was eliminated and replaced with match 9 a new loop was created, Loop 7. This loop has matches 2, 5, 6 and 9 as full members, and match 3 as a partial member. It is shown in the network obtained from Stage 13, in Figure 5.15g. The final network was obtained by optimising Loop 7. The annual cost of the final network is $79 872/year. The final network is shown in Figure 5.15h; the matches have been re-numbered.

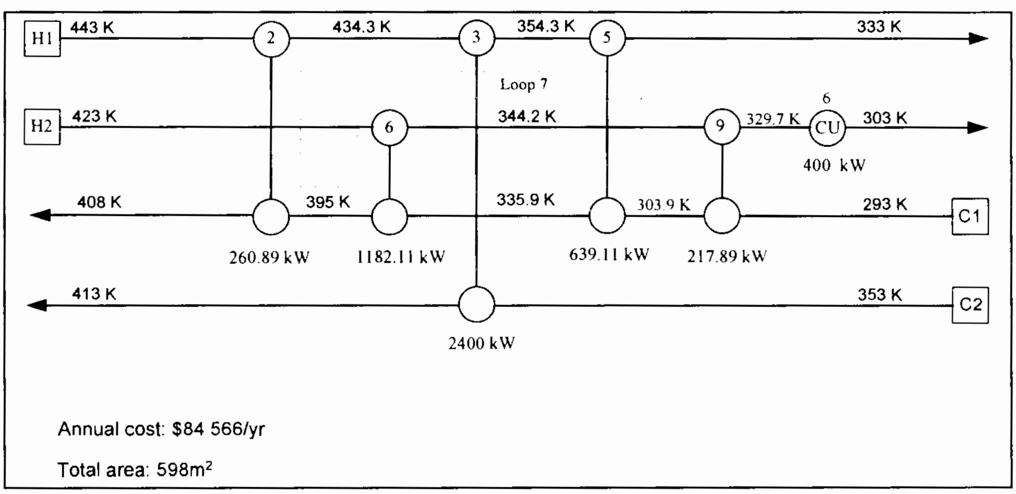

Figure 5.15g: Network structure before optimisation of Loop 7,the last loop.

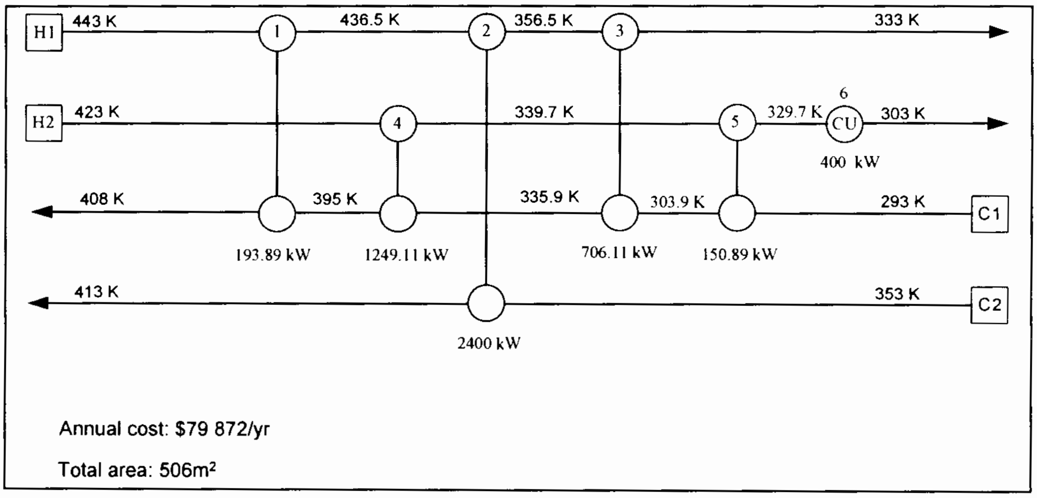

Figure 5.15h: Final network.

During evolutionary development of this problem each optimisation step led to a network annual cost that is less than or equal to (or slightly grater than) the cost obtained in the previous step. This trend is illustrated in Figure 5.17.

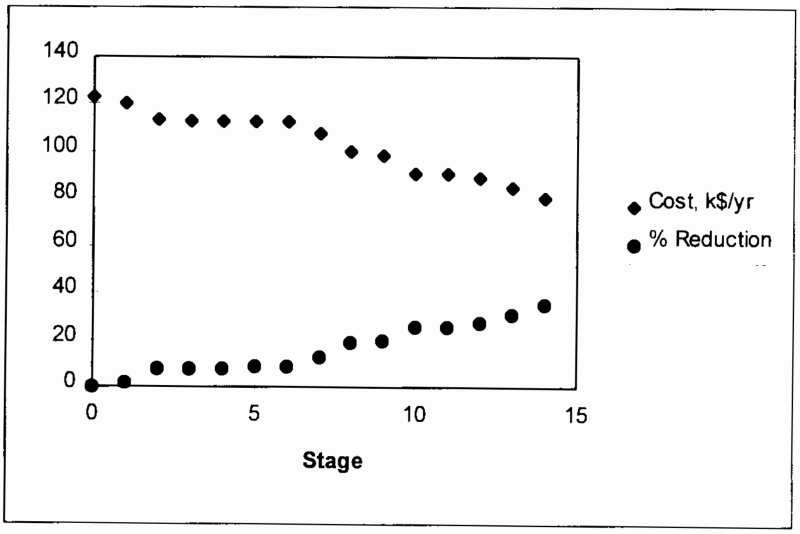

Figure 5.17: Network cost reduction during evolutionary development.

Figure 5.17 shows that as evolutionary development progressed from the initial network to the last optimisation stage the network annual cost was reduced from $122 625/year to $79 872/year. Alternatively, the network cost reduction increased from zero to about 35% of the original network annual cost of $122 625/year.

General Considerations during Evolutionary Development

It is important to note that there is no set of rigid rules that are to be applied to all network design problems. Each problem is different. Only guiding principles need to be observed and applied in a flexible manner.

The major guiding principle is that if there are paths and/or loops in a network, then they can be optimised by observing the change in the network annual cost with energy distribution along the path or around the loop. If the path or loop optimisation does not result in a reduction of the annual cost then it can be ignored, unless it leads to a step that will reduce the annual cost at a later stage.

Since paths and loops may be dependent on one another, they may be optimised more than once. No specific order has been established as to which loop should be optimised first. Paths or loops may be broken only if this leads to a reduction of the network annual cost.

New units may be created in order to achieve a structural change that lowers the network annual cost. Units can only be created as members of a path or a loop. That is, the creation of a unit involves creation of a path or a loop, and the subsequent re-distribution of energy along the path or around the loop. The ability to create new units makes it possible to move the heat load of one unit from one position to another.

If a heat load of a unit is moved from one position to another, such a move is normally made if it reduces the network annual cost. Two major considerations are taken into account: the new match site in comparison with the original position, and the path leading to the new match site or position.

The match unit cost at the new position may be lower than the match unit cost at the original position. Conditions that favour a lower match unit cost are a higher temperature driving force and a higher overall heat transfer coefficient. The first condition is determined by the temperature conditions of the streams in question. The second condition is determined by the properties of the streams.

It is to be remembered that the annual cost of a match is a function of many variables or parameters. These variables and parameters are also to be considered during structural optimisation. The ideal approach would be to allocate higher exchanger heat loads to higher temperature driving forces, higher overall heat transfer coefficients, and lower cost coefficients, and cheapest utilities in case of multiple utility problems. It is important not to lose sight of the interactions among matches. That is, conditions that ensure a lower cost for one match may make another match more expensive, and overall, the whole network more expensive.

The complex nature of network design makes it necessary to adopt a flexible approach to evolutionary development. A step performed earlier during evolutionary development, such as breaking a loop, may be reversed at a later stage if this is economically justifiable. The fact that matches can be eliminated and created at this stage of network design makes it possible, in principle, to overcome topology traps. In other words, it should be possible to change from one basic network structure to another. The only challenge is to know which conditions will lead to an optimal network. Until these conditions are known, the network designer may have to rely on knowledge of the factors that influence network optimality, physical insights such as temperature limits.

5.3. Factors Which Influence Network Optimality

The same factors that influence match optimality also influence network optimality because a match is a building block for a network. These factors are:

1. Economic parameters - cost of utilities, cost of exchangers, rate of return on investment;
2. Time parameters - life time of equipment, down time;
3. Process conditions - stream temperatures; and
4. Stream properties - heat transfer coefficients and heat capacity flowrates.

These factors are incorporated into the objective function given in Section 5.1.2 of this chapter. Additional factors that are subtle in nature are the match sequence and the network structure. No particular sequence or structure is strictly associated with network optimality. The match sequence and network structure are factors of a subtle nature because they have a a direct impact on the consumption of utilities and the allocation of temperature driving forces to exchanger heat loads. Their effects are difficult to evaluate in a precise manner and have been assessed only qualitatively.

The following section illustrates the effects of sequence and structure on network optimality. It should be borne in mind that sequence and structure are integrated with the four factors mentioned above as well as with each other, and their effects cannot be considered in isolation.

5.3.1. **Sequence Effect**

The sequence effect is a phenomenon whereby the network annual cost is affected by the order in which matches are placed in the network. The effect on cost is due to the allocation of temperature driving forces to exchanger heat loads. There are no known rules that can be followed to predict the best match sequence except careful match evaluation before placement.

The sequence effect will now be illustrated with a simple example. The stream data were taken from Linnhoff and Ahmad (1990) and the cost data were assumed. The problem is shown in Table 5.4.

Example 5.6: Illustration of the Sequence Effect.

Table 5.4: Stream data (Linnhoff and Ahmad, 1990) and cost data (assumed) used to illustrate the Sequence Effect.

Stream	T_s (°C)	T_t (°C)	F_{cp} (kW °C^{-1})
H1	170	130	1.5
H2	160	100	3.0
C1	80	140	4.0

Cost of steam = 80 \$kW^{-1}yr^{-1}

Cost of cooling water = 20 \$kW^{-1}yr^{-1}

Exchanger cost (annual basis) = \$350[A (m^2)]

Inlet temperature of cooling water = 20°C

Outlet temperature of cooling water = 60°C

Two simple solutions to this problem are shown in Figures 5.18a and 5.18b.

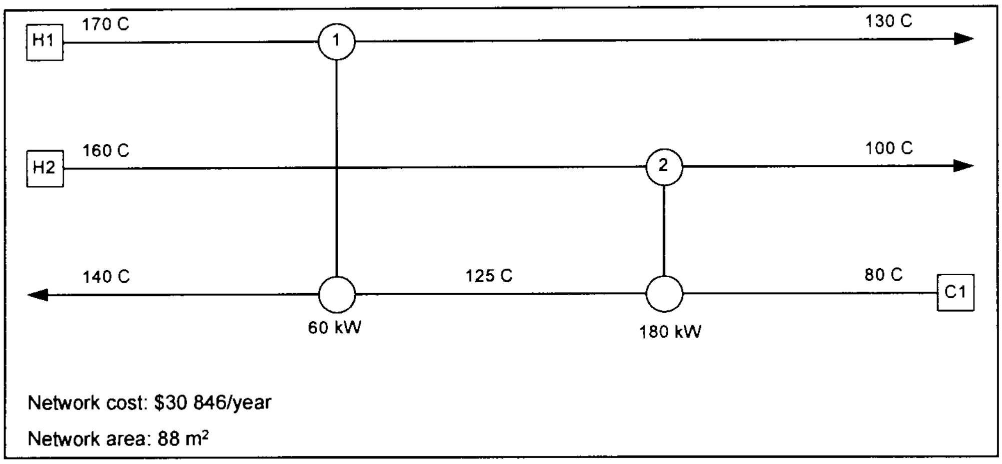

Figure 5.18a: Temperature driving forces allocated proportionately to exchanger heat loads.

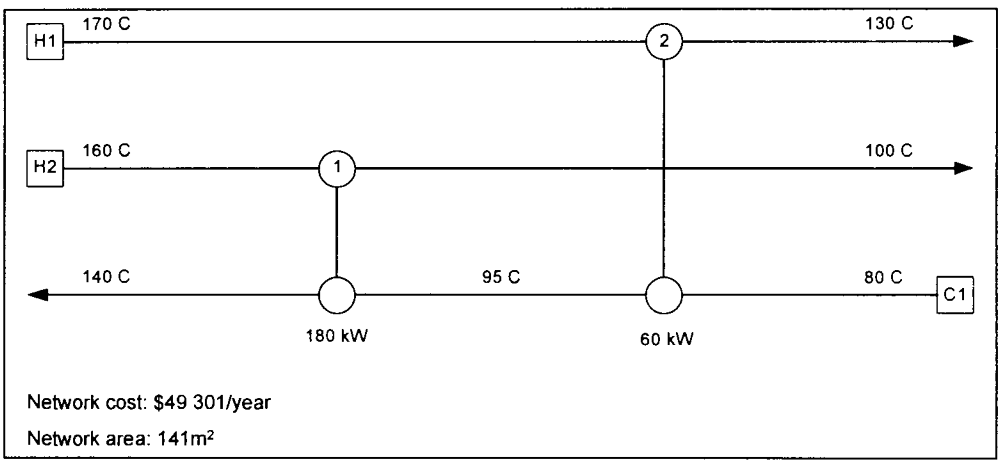

Figure 5.18b: Temperature driving forces allocated disproportionately to exchanger heat loads.

In Figure 5.18a the logarithmic mean temperature difference for match 1 is 14°C and that for match 2 is 60°C. Since match 1 has the lower heat load these temperature driving forces are proportionately allocated to the heat loads. In Figure 5.18b the logarithmic mean temperature difference for the first match is 11°C, while that for the second match is 62°C. However, the heat load of the first match is much greater than that of the second match. Hence there is a disproportionate allocation of temperature driving forces to exchanger heat loads, and it translates to a higher network annual cost.

Closely associated with the sequence effect is the effect of structure on the annual cost of a network. A brief examination of the effect of structure on network optimality is presented below.

5.3.2 **Structural Effect**

The basic structure of a network determines the extent to which the network annual cost can be reduced, say by evolution. The limitation to network evolution imposed by structure is associated with exchanger inlet and outlet temperatures. The exchanger inlet and outlet temperatures are related to exchanger heat loads. Energy exchange between any two streams is restricted to a certain temperature range compatible with thermodynamic feasibility.

This situation sometimes makes it impossible to transform one basic network structure into network structure that is globally optimal. The phrase *topology trap* has been used to describe this situation (Gundersen et. al., 1991). The topic of topology traps is not to be considered in this project, but is mentioned to highlight its significance in limiting cost reduction in network design by sequential or insight-based techniques.

Examples of the effect of structure on network optimality are given below. The solution to Example 4.2 generated in this chapter (in Example 5.5), and the solutions taken from the source of the problem are used to illustrate the effect of structure on network optimality. The problem was solved by Yee and Grossmann (1990) under four different conditions: no network restrictions; no stream splitting allowed; forbidden, required and restricted matches; and target temperatures as inequalities. To solve the problem, Yee and Grossmann (1990) used a mixed integer non-linear programming (MINLP) model to generate networks where utility cost, exchanger areas, and match selection are optimised simultaneously.

5.3.2.1 Stream splitting

The network generated by Yee and Grossmann (1990) for the situation where there are no network restrictions is shown in Figure 5.19a.

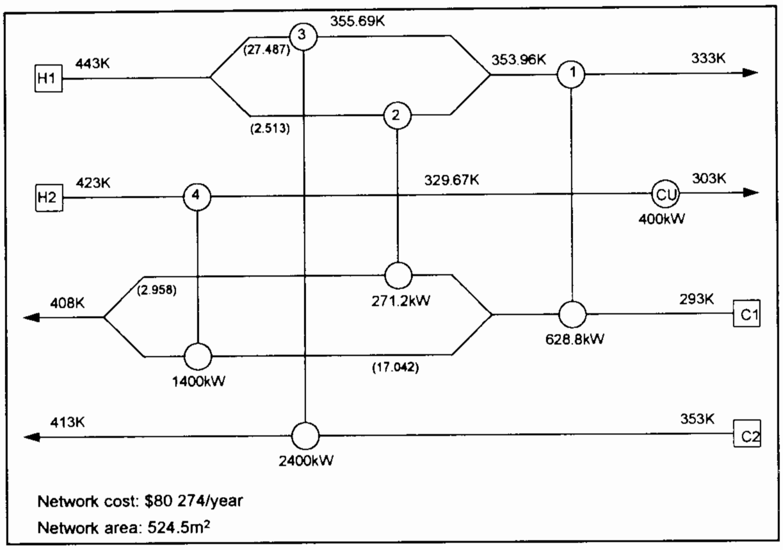

Figure 5.19a: Solution to Example 4.2 presented by Yee and Grossmann (1990) - No network restrictions.

The main feature of the network solution shown in Figure 5.19a is that it is a split network. The numbers shown in brackets are split ratios of the heat capacity flowrates. The cost of the network as reported by Yee and Grossmann (1990) is $80 274/year. This network annual cost is almost the same as that obtained for the problem in this chapter, Figure 5.15h.

The main difference between the solution presented by Yee and Grossmann (1990) and the solution obtained in this chapter is that the former involves stream splitting. The design presented by Yee and Grossmann (1990) has five units, whereas the design generated in this project has six units. It is not obvious whether there is a significant cost associated with the control aspect of the split ratios in Figure 5.19a, and split networks in general.

Yee and Grossmann (1990) have also provided a solution to this problem when no stream splitting is allowed. This solution is shown in Figure 5.19b and was obtained using MAGNETS, with a fixed heat recovery approach temperature of 10K.

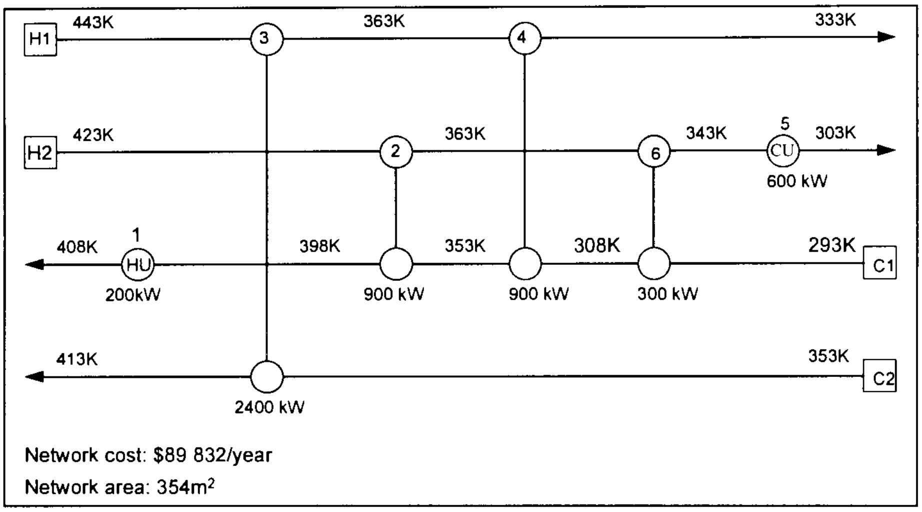

Figure 5.19b: Solution presented by Yee and Grossmann (1990) obtained by the Pinch Design method using MAGNETS.

The network shown in Figure 5.19b is about 11% more expensive than the split network shown in Figure 5.19a and the network obtained in this study.

Figure 5.15h and Figure 5.19b show some similarities: both networks do not involve stream splitting and have six units each. There are five similar matches in both networks: [H1,C2], [H2,C1], [H1,C1], [H2,C1], and [H2,CU]. The differences between Figures 5.15h and 5.19b are that Figure 5.19b has a heater as the sixth unit; while Figure 5.15h has a process match. The presence of a heater in Figure 5.19b accounts for the consumption of more than the minimum utility requirement, and consequently a higher network annual cost.

The network examples discussed in this section show that the relationship between the network annual cost and both network structure and the number of units in the network is not well defined.

5.3.2.2 Specification of an approach temperature.

If the minimum approach temperature is specified as a design requirement, it may affect network optimality. In simple terms, cheaper network designs that do not meet this design specification may not be discovered. This suggests that specification of a heat recovery approach temperature may be associated with a cost penalty. In general, the smaller the minimum approach temperature specified, the larger the number of possible network designs that can be detected.

5.3.2.3 Restrictions imposed on the network

Sometimes restrictions are imposed on the network design for practical or safety reasons. To illustrate this fact Yee and Grossmann (1990) solved the same problem when the following restrictions apply:

1. The match between H2 and cooling water is forbidden;

2. H1 needs to exchange a minimum of 300 kW with cooling water; and

3. Match [H1,C1] is restricted to a maximum of 300 kW.

Their solution is shown in Figure 5.19c.

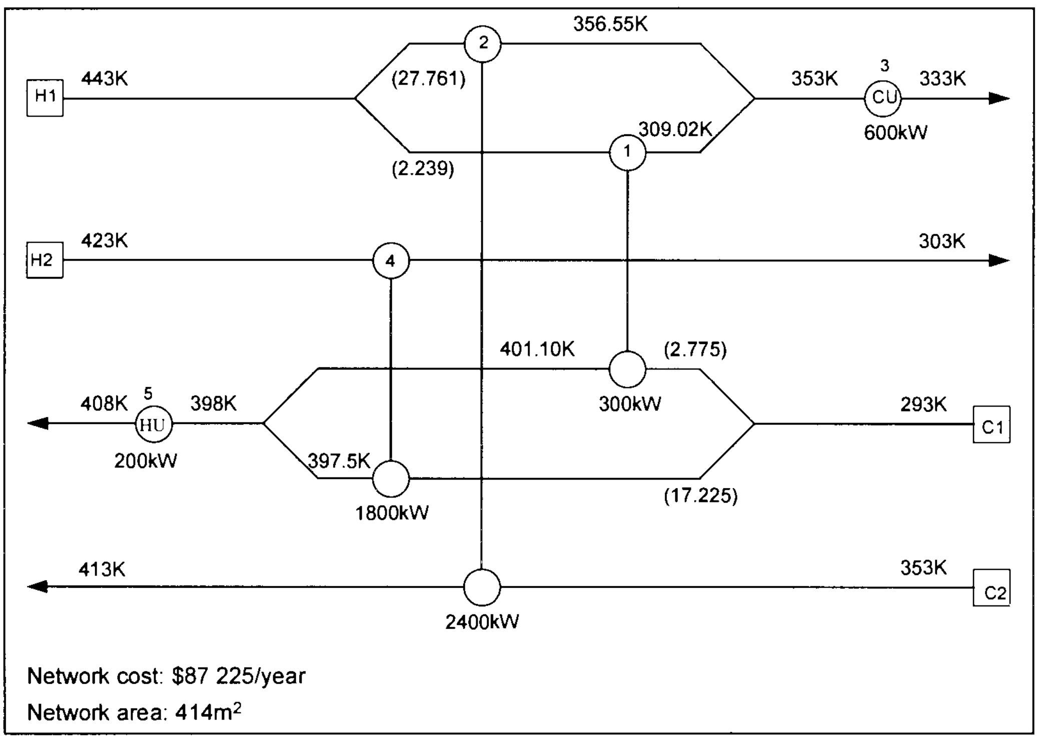

Figure 5.19c: Solution to the restricted case presented by Yee and Grossmann (1990). The forbidden match is [H2,CU]; the required match is [H1,CU]; and the restricted match is [H1,C1].

The annual cost of this network is \$87 225/year and is 9% higher than the cost of the network obtained by Yee and Grossmann (1990) when there are no restrictions. Therefore the restrictions imposed on a network design may carry a cost penalty.

5.3.2.4 Cyclic networks

Sometimes allowing two streams to exchange energy more than once can reduce the cost of a network. The result is a cyclic network. A solution to the same problem discussed above which is a cyclic network is shown in Figure 5.19d. Yee and Grossmann (1990) also generated this solution. Its total annual cost is \$80 909/year. In Figure 5.19d streams H1 and C1 exchange energy twice in matches 1 and 3.

Figure 5.19b above is also a cyclic network because streams H2 and C1 exchange energy twice, in matches 2 and 6. Yet the annual cost of the network in Figure 5.19b is \$89 832/year, which is 11% higher than the annual cost of the network in Figure 5.19d. This means that it is important to know which streams should be matched more than once, and how these streams should be matched in order to effectively reduce the network cost.

All the other networks discussed in this section are also cyclic.

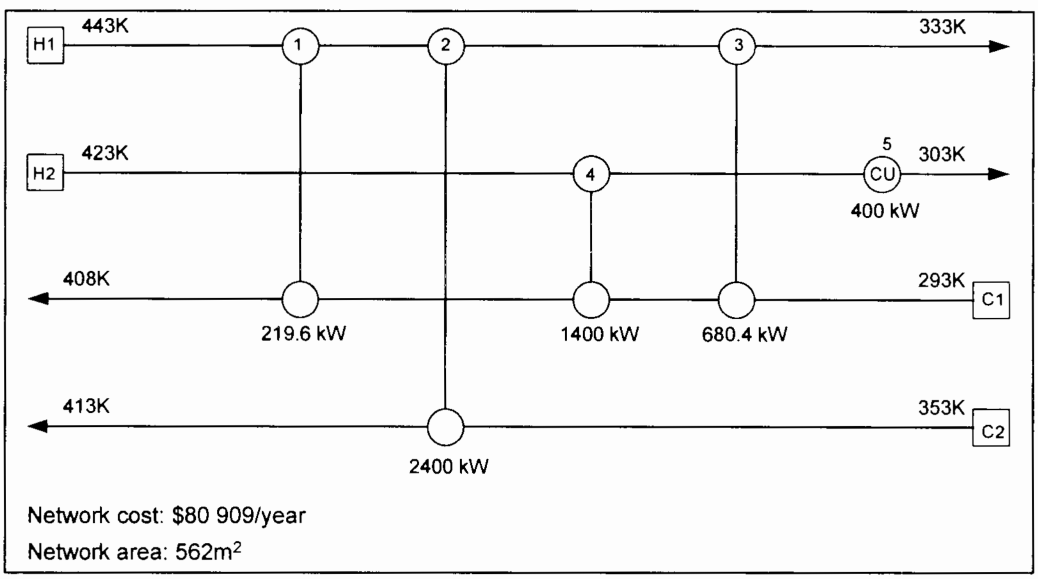

Figure 5.19d: Cyclic network generated by Yee and Grossmann (1990) as a solution to Example 4.2 when no split streams are allowed.

In a simultaneous optimisation procedure, stream splitting is performed, and cyclic networks are created, by specifying constraints that are based on a superstructure created by the designer. A computer then carries out the search for the optimum, subject to the constraints specified. In insight-based techniques there is a need for a better understanding of the interactions of all the parameters and variables involved in order to consistently generate near-optimal networks.

If the constraints and the objective function are specified well, the mathematical programming techniques generate near-optimal networks. But the derivation of a superstructure that leaves open all the match possibilities becomes complex as the problem size increases. Furthermore, the occurrence of local optima limits the proficiency of mathematical programming techniques. In order to overcome these difficulties, it may be necessary to gain better insight into the interactions of parameters and variables in network design. This insight may help the designer to channel the search for the optimum in a direction that surmounts difficulties associated with problem size.

Summary

Network optimisation in this project is performed in two major steps: match sequencing and evolutionary development.

A preliminary step called stream arrangement is included in the match sequencing stage in order to enhance energy recovery. Stream arrangement is a step in which streams are fragmented into segments within temperature intervals determined by the supply and target temperatures of cold process streams. If there is a cold process stream whose heat capacity flowrate is much higher than those of the hot process streams, then the supply and target temperatures of the hot process streams are used to determine the temperature intervals at which the cold process stream is fractured. The purpose of this design step is to use process streams as much as possible to exchange energy before utilities are used. The step also gives an indication of the absolute minimum utility requirements.

Match sequencing is concerned with the determination of the order in which streams should be matched in order to achieve an effective network cost reduction. Match selection takes into account factors that influence match optimality, namely, stream properties, stream temperatures, and economies of scale. These factors are incorporated into the match unit cost, which is used to evaluate process matches against hot utility matches. Process matches are optimised before selection. Selection of a match involves consideration of the effect of its placement on the remaining possible matches. Prioritising match selection criteria and examining other match possibilities for the streams matched does this.

Evolutionary development involves re-distribution of energy along paths and around loops. It is an effort to optimally allocate temperature driving forces to exchanger heat loads. The total annual cost of the matches that are elements of a path or loop is a unimodal function of energy distribution. Each path or loop is associated with a cost/energy curve that exhibits a minimum annual cost at a certain value of energy distributed among its elements. For some networks, it is necessary to have more than the minimum number of units to achieve the lowest network annual cost. That is, the minimum number of units is not necessarily compatible with the optimum network cost.

Although matches are components of a network, optimality of all the individual matches in the network does not necessarily lead to network optimality. An optimal network may have a match that is not optimal.

Overall, it can be deduced that the annual cost of a network can best be minimised by treating each problem according to its merits. This necessitates knowledge of the important factors that influence network optimality, namely, the heat transfer coefficient, heat capacity flowrate, temperature, cost of exchanger, cost of utilities, and network structure. Once these factors are known, it is necessary to know how they affect optimality. This knowledge can be used to develop a design strategy that leads to consistent generation of near-optimal networks.

<u>Insights gained in this phase of study</u>

Important observations made in this phase of study are listed below:

1. The two major stages defined for network optimisation are important in developing a network from the stream and cost data given to a low-cost final design. These stages

are match sequencing and evolutionary development. Stream arrangement is a preliminary step of the match sequencing stage. It is meant to ensure heat exchange between process streams before utilities are used. Match sequencing determines the order in which matches are placed in a network. The order in which matches are placed in a network affects network optimality. Evolutionary development is meant to reduce the annual cost of a preliminary network to a value that is close to the global optimum.

2. The cost correlation, stream properties, process conditions, and network structure influence network optimality.

3. Evolutionary development as described in this study is based on the network cost. Paths and loops are identified and optimised one at a time until no further cost reduction can be achieved. Matches can be eliminated or created if they are members of a path or loop. This capability makes it possible to move from one basic network structure to another.

CHAPTER 6

Implementation of the Technique

Introduction

Although the principles of the stream matching procedure described in this investigation are simple, implementation of the procedure by hand is impractical. There are too many repetitive steps that make the stream matching process tedious.

However, the simplicity of the principles used makes the procedure amenable to computer programming. It is possible to automate the whole network design procedure once it has been refined. All the problems treated in this project have been solved with the aid of a computer.

The purpose of this chapter is to give an overview of the computer programming aspect of the technique and to highlight its important features. In Section 6.1 the major data structures used in the program are described. Features of the technique that make it versatile are described in Section 6.2. An overview of the technique is given in Section 6.3. Section 6.4 gives a brief description of the application of the technique.

6.1 Data structures

The technique developed in this project involves large amounts of data. There is therefore a need to organise the data and to choose appropriate data types that will facilitate data processing. Choice of the data structures is followed by choice of the programming language that supports the data structures chosen.

A record that contains the detailed information describing the match represents each match made. Since Borland Pascal 7 supports the record data structure it was chosen as a convenient programming language. Another reason why Borland Pascal 7 was chosen is its modular structure, which allows the programmer to divide large projects into manageable pieces and then conquer each of these one by one.

In the Selection Matrix the entries are records in an array. The network designed is represented by a one-way linked list of records. The record structure used for each match made is shown in Table B.1 in Appendix B.

The computer program makes all decisions that are part of the stream-matching algorithm on the basis of the information presented in the records. Because of the capability of a record to contain dissimilar elements, some of the features of the technique are incorporated into this data structure. The features of the technique are discussed next.

6.2 Features of the Technique

The network design program has been designed to accommodate a wide range of design considerations. Considerations pertaining to economics and individual stream properties have been built into the program. This makes the program potentially flexible. Given below are a few features of the technique.

6.2.1 **Heat transfer coefficients**

The use of the record data structure makes it possible to take into account individual film coefficients. Each match has its own overall heat transfer coefficient determined by the individual film coefficients of the streams matched.

6.2.2 **Exchanger cost correlations**

Each match is allowed to have a different cost correlation. This is necessary because different exchangers may need different materials of construction, and therefore may have different costs.

6.2.3 **Equipment life-time**

The program also accommodates a situation, which may arise, in which equipment life times differ. The lifetime is used to calculate the annualised cost of a piece of equipment. This calculation is explained in Appendix B.

6.2.4 **Utilities**

Since each match is evaluated before placement in the network, utility matches can be integrated with process matches if this is economically justifiable. The program has also been made to accommodate a situation in which there are multiple utilities. Under these conditions an active utility is chosen for each match. Choosing the utility that involves the smallest match unit cost does this.

6.2.5 **Preferred and prohibited matches**

Sometimes a match may be preferred or prohibited for practical or safety reasons. To take this situation into account, the program asks the user at the beginning of the run to supply this information. This information is stored in the record for the particular match. If a match is preferred the variable *preferred* in the record assumes a value of 1; otherwise this variable is set at zero. The variable *prohibited* is treated in a similar manner.

The program matches all preferred matches before the rest of the matches are considered. Prohibited matches are not made. Before selecting any match the program checks if such a match is prohibited or not.

6.2.6 **Scope for further development**

Adding more fields in the record data structure and adjusting the computer code appropriately can extend the capability of the program. For instance, in the case of matches that involve a phase change an additional field can be added to the record data structure that will indicate the heat of transformation. Furthermore, if a match has to meet a requirement of a minimum specification such as an approach temperature or flux the minimum requirement can be specified in the record that describes the match in question.

All the situations mentioned above affect network optimality and their consideration is therefore important.

6.3 Overview of the Technique

In this technique optimisation is performed in two basic ways, match optimisation and path or loop optimisation. Match optimisation is the basis for match sequencing. Path or loop optimisation is the basis for evolutionary development. Each match is optimised before it is placed in the network. In this optimisation process the match annual cost is a function of the minimum approach temperature.

The result of match sequencing is a preliminary network that may need to be improved by path and/or loop optimisation. A brief account of the practical aspects of match optimisation, match sequencing and evolutionary development is given below.

6.3.1 Match optimisation

The match optimisation algorithm described in Chapter 3 has been converted into a computer code. The algorithm is applied to each of the twenty-six match configurations identified in Section 3.3 of Chapter 3, and there is a Borland Pascal procedure for each configuration.

The program first asks for all the information needed to define the match. Given any match to be optimised, the program identifies the particular match configuration and then selects the appropriate procedure to optimise the match. The program then stores the optimum conditions in the Selection Matrix, for each match optimised.

6.3.2 Match sequencing

The match selection criteria described in Sections 5.1.4 and 5.1.5 of Chapter 5 have been incorporated into a Borland Pascal program that performs match selection automatically. The program asks the user to supply the information needed to carry out match sequencing. The data are stored in two input files. The first input file contains stream data and the second input file contains cost data. The user is also asked to state if each possible match is preferred or prohibited.

Using the match selection criteria, the program assembles the preliminary network as a linked list of records. Each record represents a match placed in the network. The annual cost of the network and the total heat transfer surface area are also recorded.

6.3.3 Evolutionary development

Evolutionary development in this project begins with the identification of paths and loops. For smaller problems this can be done by inspection. A systematic procedure is necessary to identify paths and loops in larger network problems. Once the paths and loops are known each of them is manipulated to determine the optimum energy distribution.

This stage of the network design technique has not been automated. If performed by hand, evolutionary development as described in this project is very tedious. Automation of this process is thus essential to save time.

In the absence of a working computer program the other way of performing this task is to use a spreadsheet. Examples of a spreadsheet are Quattro Pro and Microsoft Excel. The spreadsheet used in this project was Microsoft Excel. An example of a spreadsheet is shown in Table 6.1.

In Table 6.1 the preliminary network has been presented in tabular form. If all the cells are properly defined data points can be generated by re-distributing energy along paths or around loops. Entering the energy increment dQ in the shaded cell in Table 6.1 does this. The heat load Q_r of each match in the path or loop is defined in terms of the sum of, or the difference between, the original load Q of the match and the enthalpy increment dQ. If the enthalpy increment dQ changes all the variables affected by this cell also change, as do the network annual cost and the network area.

The optimum energy distribution for each path or loop is determined by monitoring the change in the network annual cost with energy increment along the path or around the loop. The spreadsheet is updated to the optimum conditions after each path or loop has been optimised. This adjustment is made only if the network cost has been reduced during path or loop manipulation.

A match sequence can be changed during network evolution by introducing a dummy match at a different position in the network and re-distributing energy along the path or around the loop involving the dummy match. The dummy match starts off with a heat load of zero and its heat load is increased if the increase reduces the network annual cost. If the position of the dummy match is economically favourable then it becomes a real match.

Table 6.1: Example of a spreadsheet used to perform evolutionary development.

		Problem 1 - 3SP3			
		Match 1	Match 2	Match 3	
Hot stream		1	1	1	
Cold stream		1	2	0	
T_{hs}		204.4	204.4	204.4	
T_{ht}		160	160	160	
T_{cs}		126.1	126.1	37.8	
T_{ct}		160	160	82.2	
Q		206.45	258.32	3.65	
C_{hu}	37.26				
C_{cu}	17.9				
δ	0.1				
C_0	0				
C_1	1456.3				
b	0.6				
h_h		1.70342	1.70342	1.70342	
h_c		1.70342	1.70342	1.70342	
U		0.85171	0.85171	0.85171	
F_h		10.55	10.55	10.55	
F_c		6.09	7.62		
ΔH_h		468.42	468.42	468.42	
ΔH_c		206.451	258.318		
Q_r		206.45	258.32	3.65	
T_{hi}		204.4	184.8313	160.346	
T_{co}		160	160	82.2	
T_{ho}		184.8313	160.346	160	
T_{ci}		126.1	126.1	37.8	
ΔT_{he}		44.4	24.83128	78.14597	
ΔT_{ce}		58.73128	34.24597	122.2	
ΔT_{LM}		51.232	29.28685	98.53712	
A		4.731315	10.35604	0.043491	
C_A		370.0326	592.0618	22.19686	
$C_{ce\text{-}cu}$				65.335	
Tot-hu					
Tot-cu				87.53186	
C_{tot}	1049.626				
			Watch variables		
Energy balance			Increment		0
			Loop cost		370.0326
Stream	Heat load		Network cost		1049.626
H1	468.42		Network area		15.13084
C1	206.45		Original cost		1074.12
C2	258.32		Cost difference		-24.4938

6.4 Application of the Technique

In order to evaluate the technique developed in this project, twenty-three literature problems were selected. The problems feature various aspects of network design: size, individual film coefficients, match-dependent film coefficients, different exchanger cost coefficients, and multiple utilities. The solutions obtained were compared to the best designs reported in the literature available, and are presented in Chapter 7.

Summary

The network design technique developed in this project can practically be implemented with the aid of a computer. The data structures used to process the design information are an array of records and a list of records. The Selection Matrix is an array of records and the preliminary network is presented as a list of records.

The major feature of this technique is the accommodation of individual stream properties. Each match is allowed to have different: stream film coefficients, exchanger cost correlations, and equipment lifetime. Utility matches may be integrated with process matches, and multiple utilities are considered. Preferred and prohibited matches are accommodated.

The network design technique developed in this study involves match sequencing and evolutionary development. The match-sequencing algorithm has been converted into a Borland Pascal computer code. The program has been designed to accommodate future development. Evolutionary development was performed with the aid of a spreadsheet.

CHAPTER 7

Results and Discussion

Introduction

The stream matching technique developed in this project is evaluated by comparing the results obtained to network solutions that have been presented by other investigators using different techniques.

The network solutions reported in the literature are not necessarily global optima. Since the global optima for the different network problems are not known it is necessary to evaluate the solutions reported in the literature. Moreover, there are network problems whose solutions have not been reported in the literature and these solutions must also be evaluated. Unfortunately there are no known well-established network evaluation criteria that can be used to evaluate existing as well as new network solutions.

Since network evaluation criteria are necessary a few possible criteria will be examined. Possible network evaluation criteria are solutions reported in the literature, network cost targets, and network cost limits.

Desirable characteristics of a good network evaluation procedure are that it should be independent of any network design technique and that it should be derivable from the stream and cost data defining the individual problems. The ideal network evaluation criterion is the global optimum. If the global optimum cannot be found then alternative evaluation criteria need to be found. A good evaluation procedure can be used to evaluate individual network solutions as well as the design technique used to generate the solution. Although network evaluation criteria are necessary, the task of establishing standard evaluation criteria falls outside the scope of this study.

Twenty-three problems have been selected from the literature to serve as case studies in this evaluation. The problems, which range in size from three process streams to ten process streams, have been selected to cover different network features, such as different stream film coefficients, different exchanger cost correlations, and multiple utilities. The features of the individual case study problems are presented in Section 7.1. The overall results are presented in Section 7.2 and are discussed in Section 7.3.

7.1 Case Study Problems

In this section the final design solution to each of the problems is presented and briefly discussed. The stream and cost data describing the problems are listed in Appendix E.

<u>Problem 1</u> - 3SP1

This problem was taken from Liu (1987). Hohmann (1971) previously discussed it. The main features of this problem are that the size is small and the problem is relatively simple.

It involves one hot process stream, two cold process streams, one hot utility, and one cold utility. Since the objective of this project is to generate networks that are consistently near optimal it is necessary to check that the technique used can handle the simplest cases.

Hohmann (1971) and Liu (1987) used the problem as an illustrative example. No cost details of the final network design were given. In this study the problem was solved and its solution is shown as Figure 7.1.

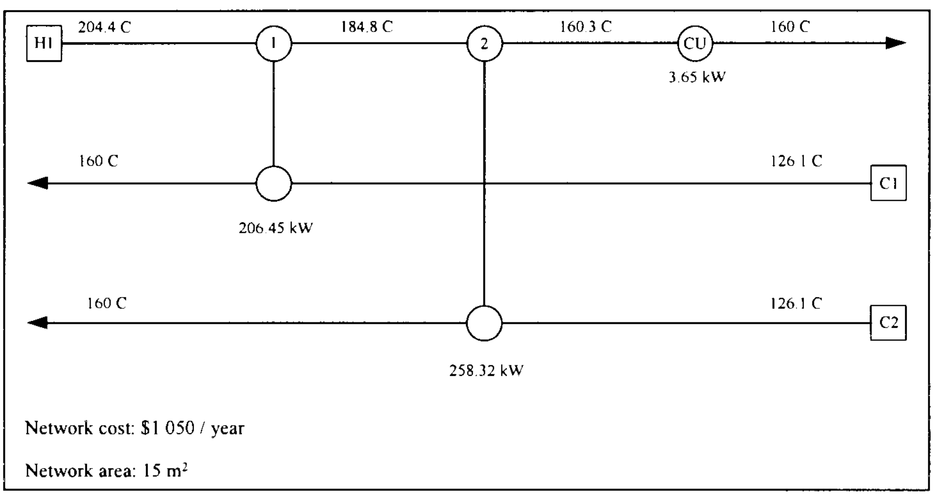

Figure 7.1: Solution to Case Study Problem 1 (3SP1).

The network solution meets the minimum utility requirement of 3.65 kW of cold utilities. The lower cost bound for this problem is \$65/year. The upper cost bound is \$26 533/year. The annual cost of the network was found to be \$1 050/year. The network performance index for this network is 0.04. If the difference between the upper cost bound and the lower cost bound is taken as a reference scale, then the annual cost obtained is closer to the lower cost bound than it is to the upper cost bound. It is about 4% away from the lower cost bound and about 96% away from the upper cost bound.

The average cost target for this problem was found to be $877/year. Therefore, the cost range ratio is 1.21.

Problem 2 – 3NIS

Nishida et al. (1977) used this problem to explain their evolutionary rules for improving a "nearly minimum cost network." They discussed the problem and provided its solution.

Like Problem 1, this problem is small and simple. It involves only three process streams. There are no utility requirements. The hot process stream can fully satisfy the energy requirements of the two cold process streams. The solution obtained in this study is shown in Figure 7.2.

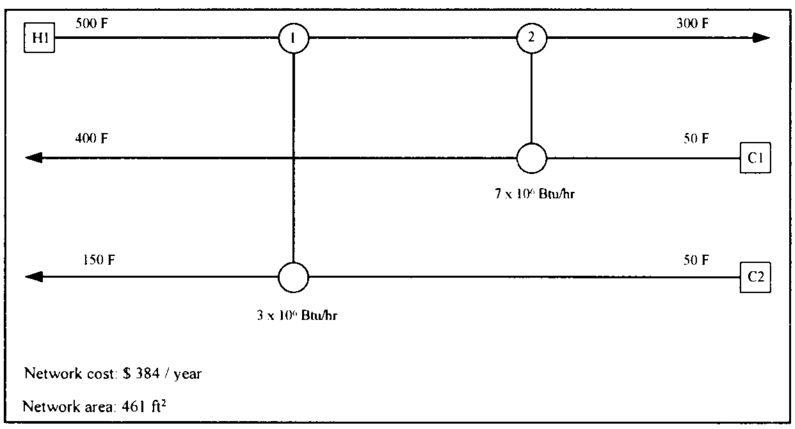

Figure 7.2: Solution to Case Study Problem 2 (3NIS).

The lower cost bound for this problem is zero since there is no utility requirement. The upper cost bound is $166 028/year. The annual cost of the network is $384/year. The network performance index is therefore 0.0023. The network annual cost is therefore very close to the lower cost bound, compared to the upper cost bound.

The average cost target for this problem was found to be \$1 328/year. The cost range ratio is therefore 0.29.

Nishida et al. (1977) obtained a final network that is quite similar to Figure 7.2, except that the match sequence was reversed. Their network structure was the same as the preliminary network obtained in this study. The annual cost of the network was \$1 475/year. The evolutionary development procedure developed in this project led to the final network shown in Figure 7.2.

<u>Problem 3</u> – 4SP1

This problem was first discussed and solved by Lee et al. (1970). The version of the problem solved in this study was taken from Liu (1987). This problem involves four process streams. There are two hot and two cold process streams, one hot utility and one cold utility. It is one of the well-known or standard literature problems. It has been solved by many workers and is therefore suitable for evaluating a new network design technique. The solution to the problem obtained in this study is shown as Figure 7.3a.

The minimum approach temperature of 11.1 °C specified by Liu (1987) was ignored. Under these conditions the smallest approach temperature occurs in match 1 of Figure 7.3a and it is 0.6 °C. The network annual cost was found to be \$10 599/year. The lower cost bound was \$7 496/year and the upper cost bound was \$105 227/year. The average cost target was found to be \$13 164/year. Therefore the network performance index is 0.03 and the cost range ratio is 0.55. Some of the solutions to the 4SP1 problem found in the literature are listed Table 7.1.

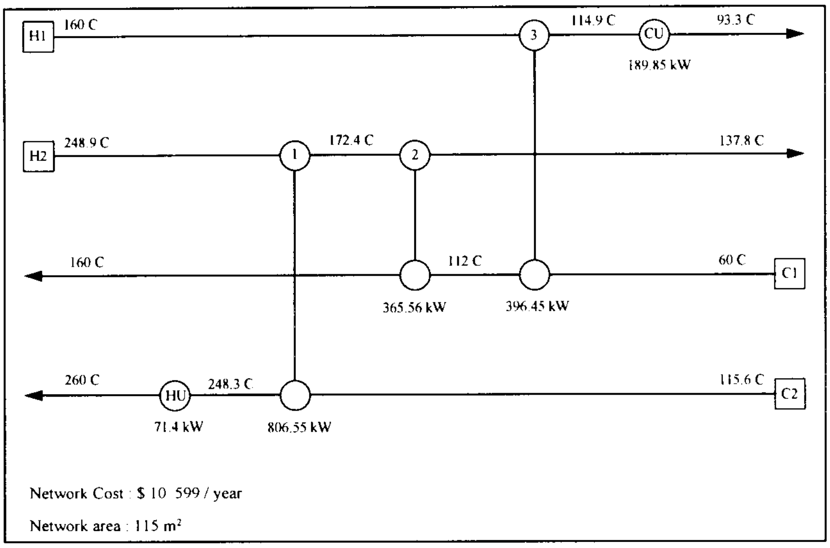

Figure 7.3a: Solution to Case Study Problem 3 (4SP1).

Table 7.1: Solutions to Problem 3 (4SP1) presented by different authors.

Author(s)	Cost, $/yr	NPI	CRR
Lee et al., 1970	13 481	0.061	1.06
Pho and Lapidus, 1973	13 685	0.063	1.09
Ponton and Donaldson, 1974	13 486	0.061	1.06
Rathore et al., 1975	13 573	0.062	1.07
Nishida et al., 1977	13 590	0.062	1.08
Linnhoff and Flower, 1978	13 587	0.062	1.07
Grossmann and Sargent, 1978	10 592	0.032	0.55
Su and Motard, 1984	13 685	0.063	1.09
Liu, 1987	13 690	0.063	1.09
Lee and Reklaitis, 1989	13 590	0.062	1.08
Yee and Grossmann, 1990	11 374	0.040	0.68
Current study (1998): ΔT_{min} = 11.1 °C	13 602	0.062	1.08
ΔT_{min} not specified	10 599	0.032	0.55

With the exception of the solutions provided by Grossmann and Sargent (1978), and Yee and Grossmann (1990), all the other solutions shown in Table 7.1 are basically the same. The slight variation is likely to be caused by round-up errors, and/or slightly different values of the minimum approach temperature such as 10 °C instead of 11.1 °C.

The solutions given by Grossmann and Sargent (1978) and Yee and Grossmann (1990) look better. These authors did not show the networks they designed. They only gave the network annual costs. It is thus not easy to see why their results are better. A possible reason is that the minimum approach temperature specified was ignored. It can be shown that the network annual cost varies with the minimum approach temperature. For the network shown in Figure 7.3a the variation of the network annual cost with the minimum approach temperature is shown in Figure 7.3b. At the minimum approach temperature of 11.1 °C specified, the annual cost of the network shown in Figure 7.3a is \$13 602/year. This network annual cost is comparable to the results obtained by other workers, shown in Table 7.1. It is also comparable to the average cost target of \$13 164/year. It can be seen that for the solution shown in Figure 7.3a the network annual cost increases with the minimum approach temperature. This means that specification of a minimum approach temperature may incur a cost penalty.

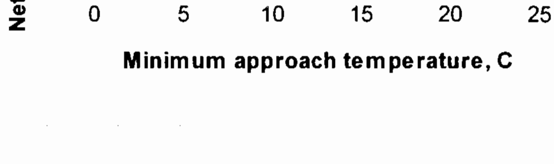

Figure 7.3b: Variation of the network annual cost with the minimum approach temperature in Figure 7.3a.

When the minimum approach temperature is not specified the annual cost of the 4SP1 problem can approach \$10 000/year. The global optimum cost for the network is in the range of \$7 496/year to \$10 592/year. The first figure is the lower cost bound and the second figure is the annual cost reported by Grossmann and Sargent (1978). Whatever the value of the global optimum is, it is very close to the rest of the results shown in Figure 7.1 compared to the upper cost limit of \$105 227/year. All the results shown in Table 7.1 can therefore be taken as near optimal, taking into account possible constraints imposed by the individual workers.

Problem 4 – 4SP2

Ponton and Donaldson (1974) introduced this problem. It involves three hot process streams, one cold process stream, one hot utility, and one cold utility. Its main feature is that it involves a cold process stream whose heat capacity flowrate is markedly greater than the heat capacity flowrates of the three hot process streams.

Ponton and Donaldson (1974) presented two solutions to the problem: an acyclic network by a branch and bound method, and a cyclic network by their heuristic method. They realised that the annual cost of the acyclic network (\$63 694/year) was almost three times as large as the annual cost of the cyclic network (\$23 724/year). Although these workers provided the solutions, no cost data were given. Instead, the reader was referred to the cost data provided for the problem 7SP1 by Pho and Lapidus (1973). The version of the problem solved in this study was taken from Liu (1987). The network solution is shown in Figure 7.4.

The annual cost of the network shown in Figure 7.4 was found to be \$21 144/year. The lower cost bound for this problem was \$12 552/year. The upper cost bound was \$400 219/year and the average cost target was \$26 143/year. Therefore the network performance index is 0.022 and the cost range ratio is 0.63. Different workers have solved this problem and some of the solutions reported in the literature are shown in Table 7.2.

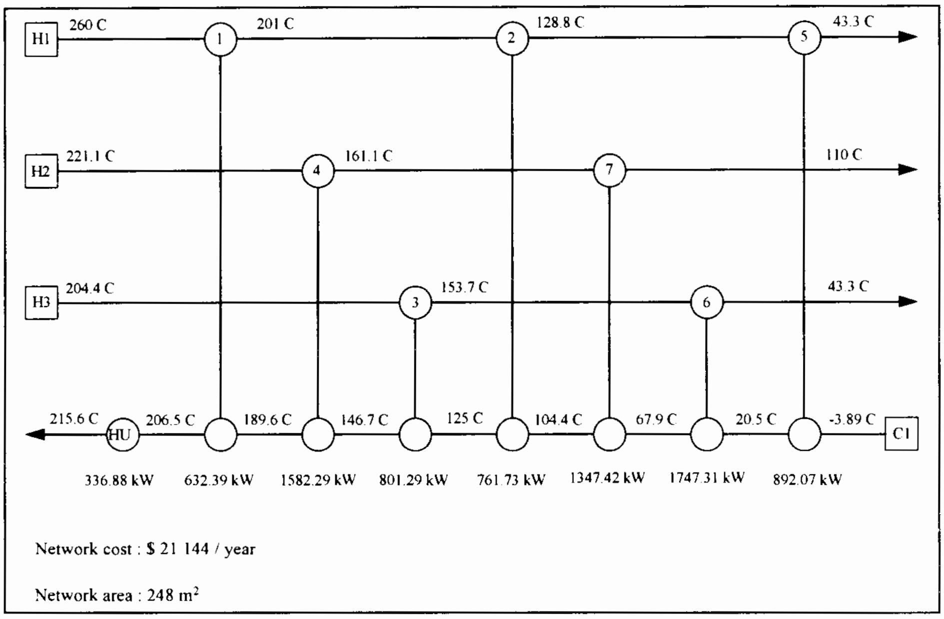

Figure 7.4: Solution to Case Study Problem 4 (4SP2).

Table 7.2: Solutions to Problem 4 (4SP2) presented by different authors.

Author(s)	Cost, $/yr	NPI	CRR
Ponton and Donaldson, 1974	23 724	0.029	0.82
Nishida et al., 1977	20 353	0.020	0.57
Linnhoff and Flower, 1978	19 571	0.018	0.52
Grossmann and Sargent, 1978	21 663	0.024	0.67
Grimes et al., 1982	19 141	0.017	0.48
Su and Motard, 1984	19 647	0.018	0.52
Liu, 1987	19 571	0.018	0.52
Lee and Reklaitis, 1989	19 454	0.018	0.51
Current study, 1998	21 144	0.022	0.63

All the networks whose costs are lower than \$21 000/year involve stream splitting. This suggests that stream splitting can sometimes lower the network annual cost.

All the results shown in Table 7.2 are reasonable because each network annual cost is much closer to the lower cost bound than it is to the upper cost bound. All the network annual costs are also lower than the average cost target. The differences among the individual annual cost values can mainly be attributed to stream splitting. Split networks in this particular example are cheaper than the networks that do not involve stream splitting. This is only true if there is no significant cost associated with the installation of process control equipment. Process control would normally be required to maintain the split ratios of the streams.

The networks whose annual costs are shown in Table 7.2 were either cyclic or split network structures. One of the networks, presented by Nishida et al. (1977), was both a cyclic and split network.

Problem 5 – 4TC2

Linnhoff and Flower (1978) introduced this problem as a test case. The problem involves two hot process streams, two cold process streams, one hot utility, and one cold utility. These workers only presented the preliminary network without optimising it. The annual cost of their preliminary network was \$17 560/year. The solution to the problem obtained in this study is shown in Figure 7.5.

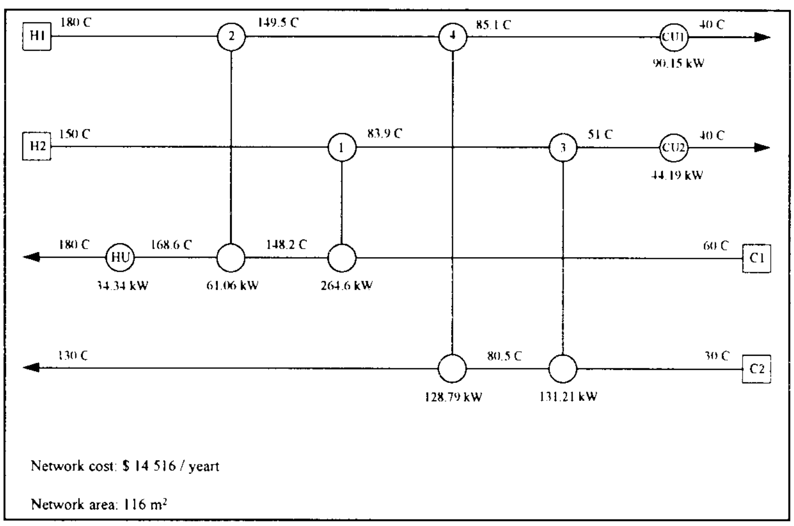

Figure 7.5: Solution to Case Study Problem 5 (4TC2).

The network annual cost was found to be \$14 516/year. To get this result, the minimum approach temperature of 10 °C specified was ignored.

The lower cost bound for this problem was \$2 194/year and the upper cost bound was \$86 823/year. The average cost target was \$5 713/year. The network performance index was therefore 0.15 and the cost range ratio was 3.50. Three results obtained from the literature are shown in Table 7.3.

Table 7.3: Solutions to Problem 5 (4TC2) presented by different authors.

Author(s)	Cost, \$/yr	NPI	CRR
Linnhoff and Flower, 1978	17 560	0.182	4.37
Su and Motard, 1984	16 690	0.171	4.12
Lee and Reklaitis, 1989	16 173	0.165	3.97
Current study, 1998: ΔT_{min} not specified	14 516	0.146	3.50
ΔT_{min} = 10 °C	18 269	0.190	4.57

When the minimum approach temperature was increased to 10 °C in Figure 7.5, the network annual cost increased from \$14 516/year to \$18 269/year. Su and Motard (1984) obtained their result by splitting streams. Lee and Reklaitis (1989) did not show the network structure. The results obtained in this study confirm the fact that specification of a minimum approach temperature may incur a cost penalty. The results obtained in this study are comparable to those reported in the literature. All the results shown in Table 7.3 are much higher than the average cost target. This may suggest that the average cost target found is not realistic or achievable, or that all the results reported in Table 7.3 are poor.

<u>**Problem 6**</u> – 4YEE1

This problem involves two hot process streams, two cold process streams, one hot utility, and one cold utility. It was taken from Yee and Grossmann (1990). Gundersen and Grossmann (1990), and Colberg and Morari (1990) also studied it. All these workers determined the capital cost of the network. The total network cost was calculated in this study using a unit cost of $80/kW for hot utilities and $20/kW for cold utilities. The network solution obtained in this study is shown in Figure 7.6a.

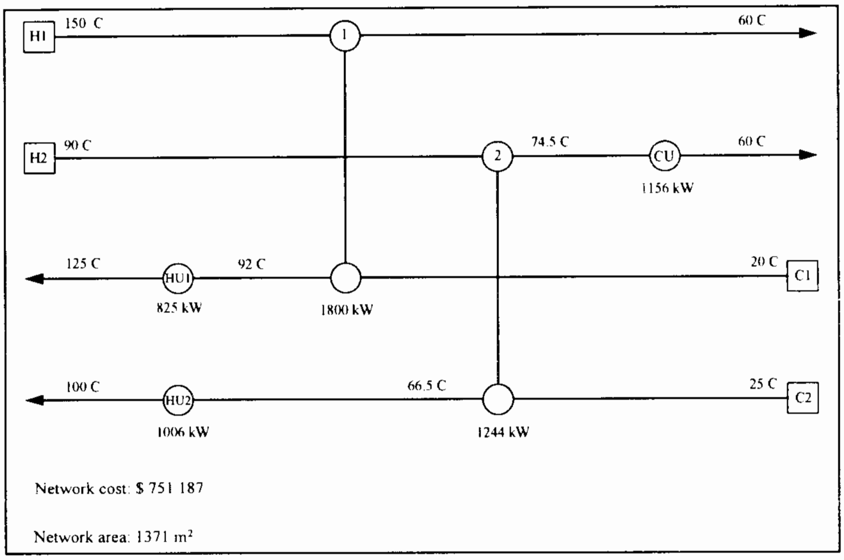

Figure 7.6a: Solution to Case Study Problem 6 (4YEE1).

The total cost of the network was found to be $751 187. The lower cost bound was $54 000 and the upper cost bound was $795 773. The average cost target was $561 433. The network performance index was 0.94 and the cost range ratio was 1.37. The results obtained from the literature are shown in Table 7.4.

Table 7.4: Solutions to Problem 6 (4YEE1) presented by different authors.

Author(s)	Cost, $		NPI	CRR
	Capital	Total		
Gundersen and Grossmann, 1990	729 000	823 000	1.04	1.52
Colberg and Morari, 1990	729 000	823 000	1.04	1.52
Yee and Grossmann, 1990	715 970	809 970	1.02	1.49
Current study, 1998	581 587	751 187	0.94	1.37

Since the values of the network performance index shown in Table 7.4 are greater than 0.5 it means that each of the network costs in the table is closer to the upper cost bound than it is to the lower cost bound. A network performance index that is greater than one indicates a network cost that is higher than the upper cost bound. This situation is not easy to justify economically. However, it can exist if the upper cost bound is not determined before or during network design. The designer may not even be aware of the fact that the network cost is higher than the upper cost bound.

It is possible to design a network whose cost is not less than the upper cost bound. For instance, such a situation could arise if all the cold process streams have supply temperatures that are equal to or higher than the supply temperatures of the hot process streams. Under such conditions the temperature requirements can only be met by supplying utilities and the network annual cost would be equal to the upper cost bound.

An exchanger cost correlation that involves large coefficients could lead to a network design whose annual cost is equal to or higher than the upper cost bound. Under these circumstances the network annual cost can be equal to or greater than the upper cost bound even if the minimum utility requirements are met. This situation explains the results obtained from the literature in Table 7.4.

All the results obtained from the literature in Table 7.4 were based on a heat recovery approach temperature (HRAT) of 20 °C and the minimum requirements of 400 kW of cold utilities and 1075 kW of hot utilities. The exchanger cost correlation for the problem was $8600 + 670A^{0.83}$. The literature results shown in Table 7.4 suggest that, with this cost correlation, if the utility consumption is minimised then the network cost can exceed the upper cost bound. This means that no cost savings are achieved even though maximum energy recovery is achieved. This example illustrates the importance of monitoring the trade-off between the annual cost of capital and the annual cost of energy during design.

The network solution obtained in this study involves 1156 kW of cold utilities and a total of 1831 kW of hot utilities. This utility consumption is 756 kW higher than the minimum utility requirement. Yet the network annual cost is just below the upper cost bound. The use of more than the minimum utilities required has reduced the heat transfer surface area in the process exchangers. The higher temperature driving forces restrained the increase in the heat transfer surface area of the utility exchangers.

Since the cost of utilities was not specified in the original problem, it would be advisable to examine the effect of the cost of utilities on the total network costs shown in Table 7.4. Assume the network designs are complete and the cost of utilities varies over the ranges of \$10/kW to \$100/kW for the cold utility and \$40/kW to \$400/kW.for the hot utility.

The variation of the total annual cost of the fixed designs reported in Table 7.4 with the cost of utilities is illustrated in Figure 7.6b. The symbols GG stand for the design presented by Gundersen and Grossmann (1990) in Table 7.4. The symbols CM, YG, and CS refer to the designs obtained by Colberg and Morari (1990), Yee and Grossmann (1990), and the current study. The variation of the total network cost with the cost of utilities was obtained by adding an arbitrary value of the cost of utilities at each stage to get a value at the successive stage. The arbitrary increments of the unit costs were \$10/kW for the cold utility and \$40/kW for the hot utility. At each stage the total cost of the hot and cold utilities were obtained by multiplying the utility requirement (fixed for each design) with the unit utility cost and adding the costs of both the hot and cold utilities to the appropriate capital cost at each stage. The cost of capital was fixed at the value shown in Table 7.4 for each design. The increase in the cost of utilities was expressed as the percentage of the starting values.

It can be seen that when the cost of capital is much higher than the cost of utilities minimisation of the utility consumption can result in a network cost that exceeds the upper cost bound. This observation is in agreement with the whole concept of the trade-off between the cost of energy and the cost of capital.

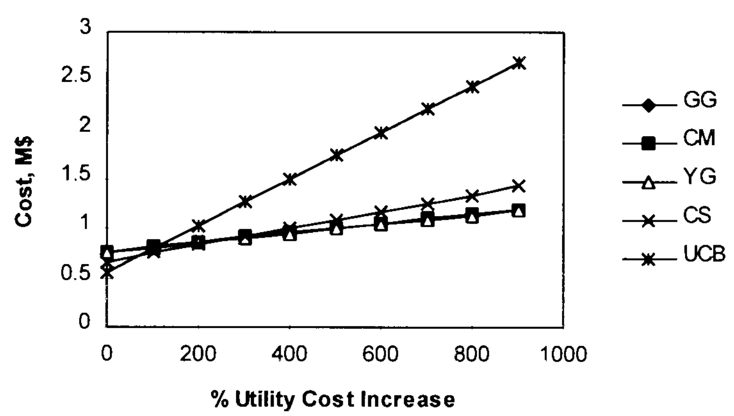

Figure 7.6b: Variation of the total network cost with the cost of utilities for the fixed designs whose costs are shown in Table 7.4.

An interesting observation to be made in Figure 7.6b is that a design that is cheaper than another design at one (present) level of the cost of utilities may be more expensive than the same design at another (future) level of the cost of utilities.

Problem 7 – 4YEE2

This problem involves two hot process streams, two cold process streams, one hot utility, and one cold utility. It was taken from Yee et al. (1990). Its main feature is that the heat transfer coefficients may differ by an order of magnitude. The solution to the problem obtained in this study is shown in Figure 7.7.

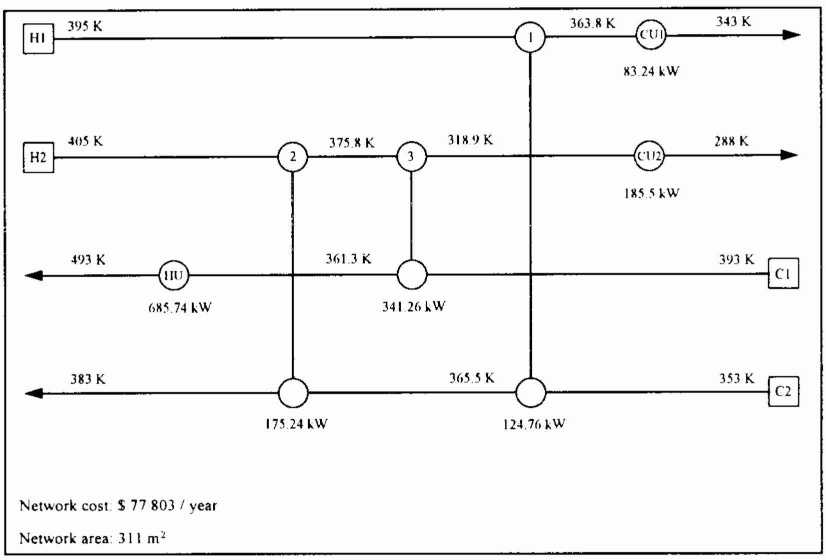

Figure 7.7: Solution to Case Study Problem 7 (4YEE2).

The annual cost of the network was found to be $77 803/year. The lower cost bound was $36 200/year and the upper cost bound was $133 476/year. The average cost target was $53 590/year. The network performance index was found to be 0.43 and the cost range ratio was 2.39. While savings achieved were appreciable, the network annual cost was significantly higher than the average cost target.

Yee et al. (1990) determined cost targets for this problem. They did not present the network design. The design conditions used in this study involved a unit cost of $80/(kW.yr) for the hot utility, $20/(kW.yr) for the cold utility, and a linear cost correlation of one hundred times the heat transfer surface area (C = 100A). The cost target obtained by Yee et al. (1990) under these conditions was $79 850/year. The case selected in this study was unrestricted.

It will be noted that the network cost obtained is less than the cost target reported by Yee et al. (1990) even though it is higher than the average cost target determined in this study. This situation illustrates the uncertainty associated with network design targets, namely, how realistic they are.

Problem 8 – 4YEE3

This problem involves two hot process streams, two cold process streams, one hot utility, and one cold utility. It was taken from Yee and Grossmann (1990). It was previously discussed by Linnhoff et al. (1982). The main feature of this problem in the form presented by Yee and Grossmann (1990) is that the overall heat transfer coefficient and the cost correlation involving heaters are different from those involving the rest of the exchangers. The current solution is shown in Figure 7.8.

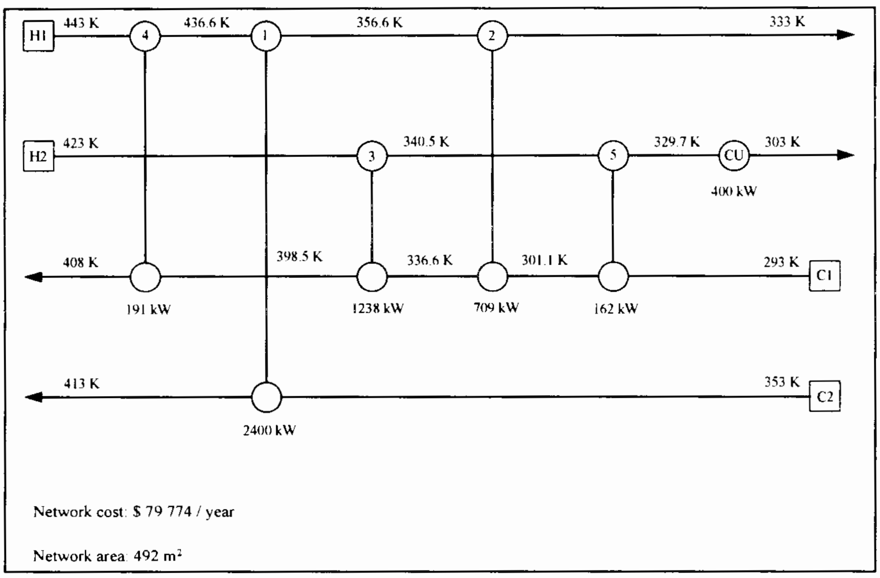

Figure 7.8: Solution to Case Study Problem 8 (4YEE3).

The problem was solved for the situation in which no network restrictions were imposed. The annual cost of the network was $79 774/year. The lower cost bound was $8 000/year and the upper cost bound was $521 609/year. The average cost target was $88 095/year. Thus, the network performance index was 0.14 and the cost range ratio was 0.9. The results reported in the literature are shown in Table 7.5.

Table 7.5: Solutions to Problem 8 (4YEE3) presented by different authors.

Author(s)	Cost, $/yr	NPI	CRR
Yee and Grossmann, 1990	80 274	0.141	0.902
Byfield and Ang, 1994	79 429	0.139	0.892
Zhu et al., 1995	80 815	0.142	0.909
Current study, 1998	79 774	0.140	0.897

The network annual costs shown in Table 7.5 are almost the same; they differ by less than 2%.

Problem 9 - 4FRAS

This problem involves two hot process streams, two cold process streams, one hot utility, and one cold utility. Fraser (1994) discussed it to illustrate handling of utilities in Heat Exchanger Network Synthesis. The problem was not solved; only the cost target was presented. In this study the problem was solved and the solution is shown in Figure 7.9.

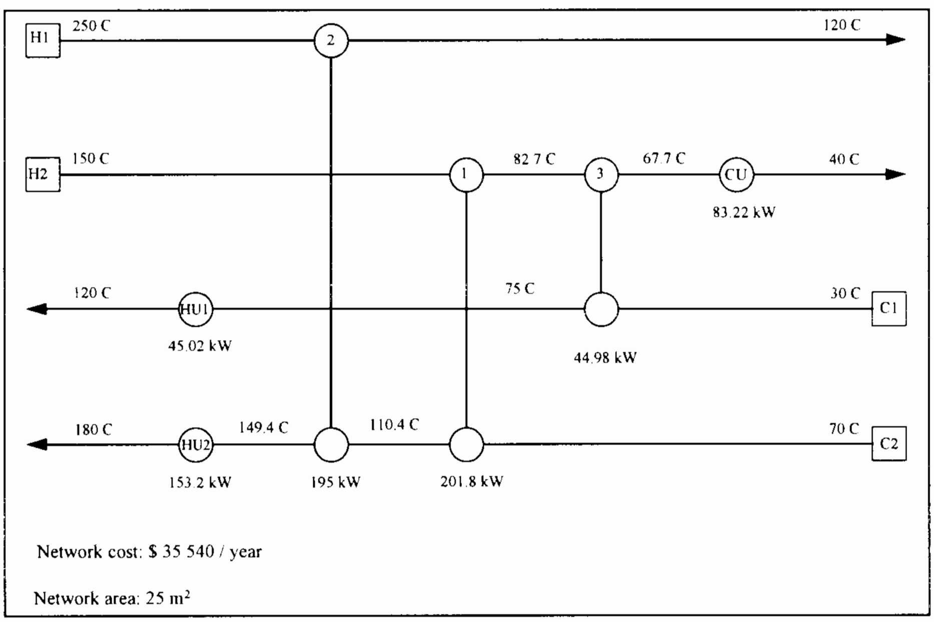

Figure 7.9: Solution to Case Study Problem 9 (4FRAS).

The network annual cost was found to be \$35 540/year. The lower cost bound was \$8 913/year and the upper cost bound was \$72 004/year. The average cost target was \$19 716/year. The network performance index was therefore 0.42 and the cost range ratio was 2.46.

The cost target given by Fraser (1994) was \$45 296/year. This value was determined on the basis of a minimum approach temperature of 10°C by the Pinch Design Method. The annual cost of the network shown in Figure 7.9 at this value of the minimum approach temperature is \$35 616/year. The cost target reported by Fraser (1994) is at least twice as large as the average cost target obtained in this study. This observation gives further evidence that network design targets may differ widely, and depend on the design technique used. It can be concluded, therefore, that network cost targets are not a reliable reference for the evaluation of network performance.

Problem 10 – 5SP1

Masso and Rudd (1969) introduced this problem. It involves two hot process streams, two cold process streams, one hot utility, and one cold utility. The solution obtained in this study is shown in Figure 7.10.

The annual cost of the network was \$38 964/year. The lower cost bound was \$33 368/year and the upper cost bound of \$260 264/year. The average cost target was \$40 333/year. The network performance index was 0.0247 and the cost range ratio was 0.80. The version of the problem solved in this study was taken from Liu (1987). Other solutions to the problem are shown in Table 7.6.

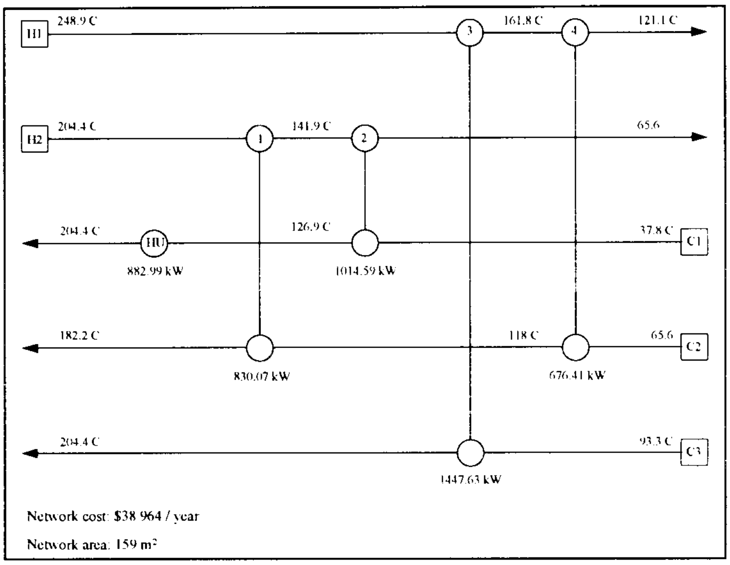

Figure 7.10: Solution to Case Study Problem 10 (5SP1).

Table 7.6: Solutions to Problem 10 (5SP1) presented by different authors.

Author(s)	Cost, $/yr	NPI	CRR
Masso and Rudd, 1969	38 745	0.024	0.77
Lee et al., 1970	38 278	0.022	0.70
Pho and Lapidus, 1973	38 268	0.022	0.70
Nishida et al., 1977	38 713	0.024	0.77
Linnhoff and Flower, 1978	38 519	0.023	0.74
Grossmann and Sargent, 1978	38 288	0.022	0.71
Flower and Linnhoff, 1980	38 278	0.022	0.70
Grimes et al., 1982	39 706	0.028	0.91
Su and Motard, 1984	38 268	0.022	0.70
Dolan et al., 1989	39 440	0.027	0.87
Lee and Reklaitis, 1989	38 712	0.024	0.77
Current study, 1998	38 964	0.025	0.80

Although the results shown in Table 7.6 differ by a maximum of only 4% the conditions under which they were obtained were not strictly the same. Some workers (Masso and Rudd, 1969; and Nishida et al., 1977) specified a downtime of 260 hours/year, others (Lee et al., 1970; and Pho and Lapidus, 1973) specified a downtime of 380 hours/year. The rest of the results were based on either of these two downtimes. In this study a downtime of 380 hours/year was used and the network annual cost was found to be \$38 964/year. If the downtime were chosen to be 260 hours/year the network annual cost would be \$38 487/year. Other workers (Grimes et al., 1982; and Dolan et al., 1989) solved the problem for the situation in which a match between one hot stream (supply temperature 204.4 °C) and a cold stream (supply temperature 37.8 °C) was prohibited.

Twelve different solutions presented by different workers using different methods seem to indicate that the global optimum could be at least \$38 000/year.

Problem 11 – 5ZHU

This problem involves three hot process streams, two cold process streams, one hot utility, and one cold utility. The main feature of this problem is that the stream film coefficients differ by as much as a factor of 50. The stream data can be traced back to Ahmad's thesis (1985), in which it was discussed as an example (Example 7.10) and no cost data were given. Other workers who modified and discussed this problem are Ahmad et al. (1990), Gundersen and Grossmann (1990), Rev and Fonyo (1991), and Zhu et al. (1995). In this study the problem was solved in the form presented by Zhu et al. (1995). The solution obtained in this study is shown in Figure 7.11a.

The network annual cost was found to be \$56 443/year. The lower cost bound was \$2 295/year and the upper cost bound was \$72 736/year. The average cost target was \$67 443/year. Hence, the network performance index was 0.769 and the cost range ratio was 0.83.

The network annual cost reported by Zhu et al. (1995) is \$46 551/year. Their network is shown in Figure 7.11b.

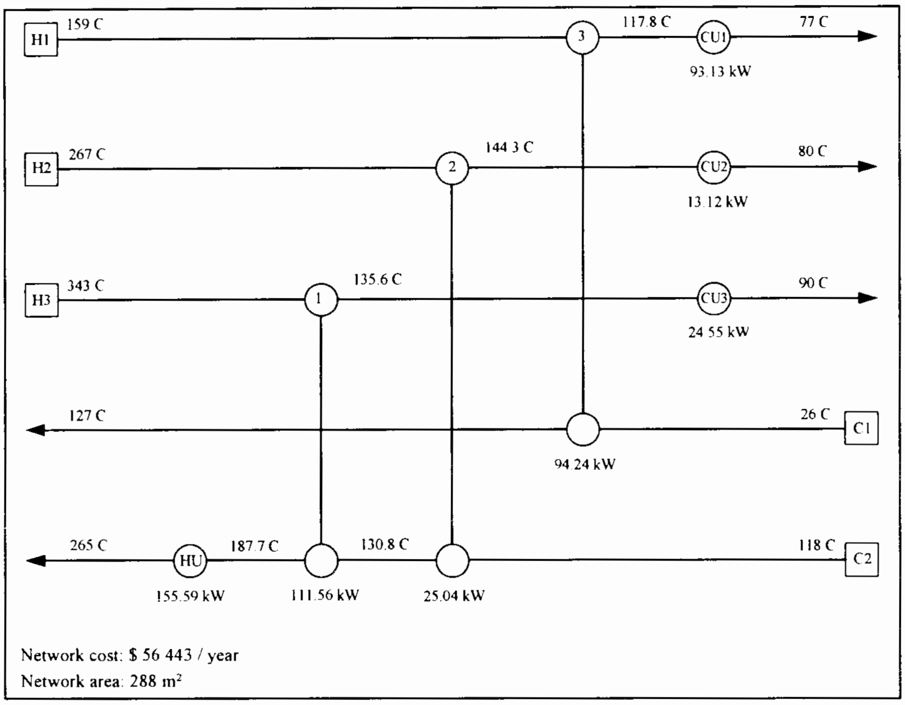

Figure 7.11a: Solution to Case Study Problem 11 (5ZHU).

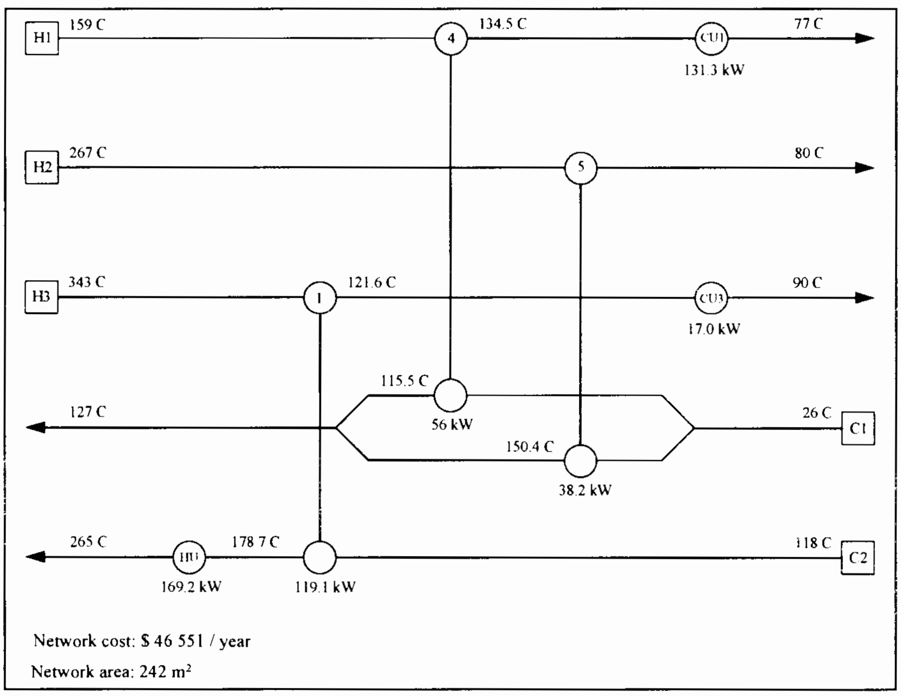

Figure 7.11b: Solution to Case Study Problem 11 presented by Zhu et al. (1995).

It is not clear how the annual cost of $46 551/year was reached. The annual cost for the network in Figure 7.11b was calculated in this study to be $54 131/year. This annual cost was reached by using the rate of return on investment calculated by Equation *C-i.1* in Appendix C. The network annual cost of $54 131/year calculated in this work for the network structure presented by Zhu et al. (1995) will be used for comparison. This network annual cost is 4% lower than the solution presented in this study.

Problem 12 - 6SP1

This problem involves three hot process streams, three cold process streams, one hot utility, and one cold utility. Lee et al. (1970) introduced it. The version of this problem solved in this study was taken from Liu (1987). The solution found in this study is shown in Figure 7.12.

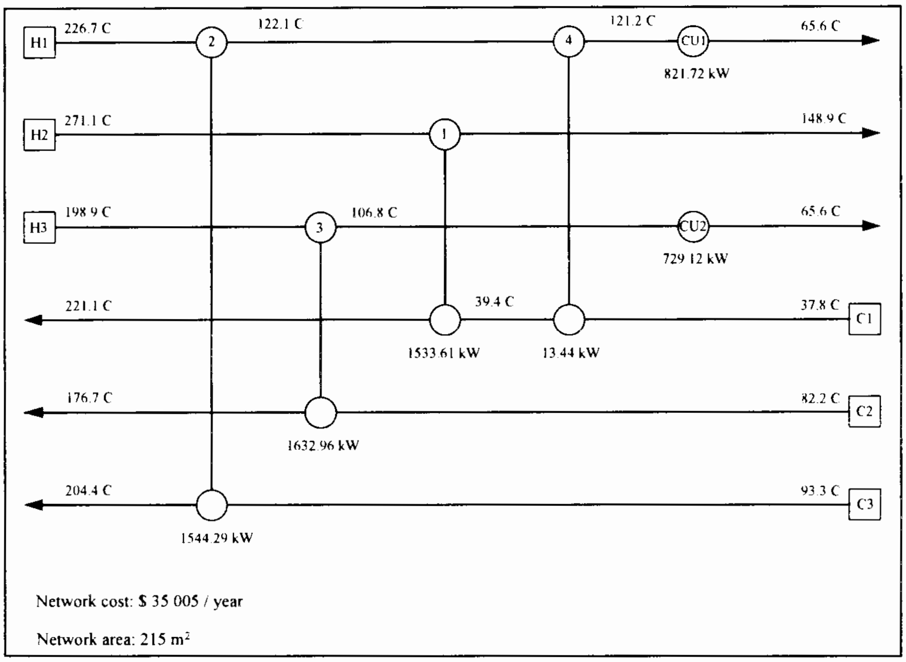

Figure 7.12: Solution to Case Study Problem 12 (6SP1).

The annual cost of the network shown in Figure 7.12 is $35 005/year. The lower cost bound was $27 760/year and the upper cost bound was $294 190/year. The average cost target was $33 865/year. The network performance index was therefore 0.027 and the cost range ratio was 1.19.

A number of workers have solved this problem. Their solutions are shown in Table 7.7. The result obtained in this study was similar to some of the results reported in the literature. The slight difference in the annual network costs is due to rounding up of figures. From the results shown in Table 7.7 it can be speculated that the global optimum for this problem is around $35 000/year.

If the global optimum is at least \$35 000/year then the average cost target calculated in this study, \$33 865/year, cannot be achieved. This shows that cost targets may not be reliable for measuring network performance. For this problem no cost targets were found in the literature available. Cost targets, therefore, should be viewed with caution; they can only be used as guidelines.

Table 7.7: Solutions to Problem 12 (6SP1) presented by different authors.

Author(s)	Cost, \$/yr	NPI	CRR
Lee et al., 1970	35 108	0.0275	1.20
Hohmann, 1971	35 010	0.0272	1.19
Pho and Lapidus, 1973	35 659	0.0296	1.29
Ponton and Donaldson, 1974	35 407	0.0287	1.25
Nishida et al., 1977	35 010	0.0272	1.19
Linnhoff and Flower, 1978	35 010	0.0272	1.19
Grossmann and Sargent, 1978	35 010	0.0272	1.19
Su and Motard, 1984	35 010	0.0272	1.19
Lee and Reklaitis, 1989	35 010	0.0272	1.19
Current study, 1998	35 005	0.0272	1.19

Problem 13 - 6YEE

The situation in which one process stream has a heat capacity flowrate that is much larger than that of the process streams of the opposite type is once again considered in this example. Yee and Grossmann (1990) discussed this problem. It involves five hot process streams, one cold process stream, one hot utility, and one cold utility. According to Yee and Grossmann (1990) split streams are required in this situation. However, in this study the problem was solved without stream splitting and the solution is shown in Figure 7.13a. The network is cyclic.

The annual cost of the network was found to be \$605 263/year. The lower cost bound was \$484 400/year and the upper cost bound was \$1 007 539/year. The average cost target was

$544 481/year. Hence, the network performance index was 0.23 and the cost range ratio was 2.01.

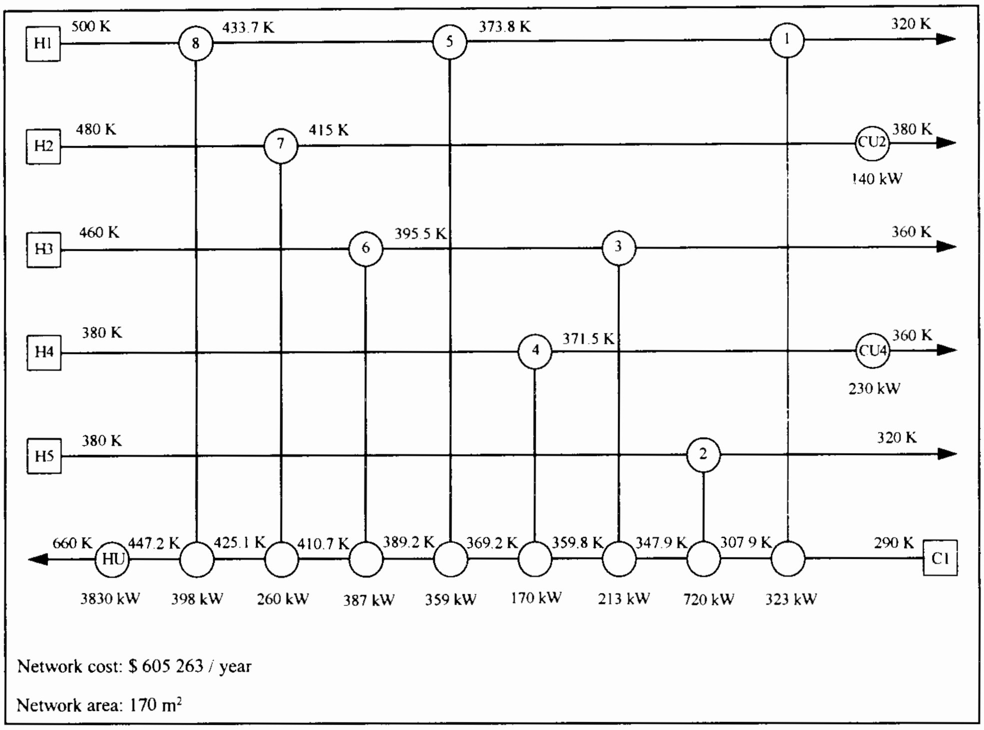

Figure 7.13a: Solution to Case Study Problem 13 (6YEE).

The cheapest design presented by Yee and Grossmann (1990) is shown in Figure 7.13b. It is a cyclic split network. The annual cost of this network was reported as $575 595/year. For this solution the network performance index is 0.174 and the cost range ratio is 1.52. The solution obtained in this study is about 5% higher than that obtained by Yee and Grossmann (1990). However, the complexity of the network presented by Yee and Grossmann (1990) might necessitate some control over the split ratios. The split ratios are shown as numbers in brackets in Figure 13b.

The capital cost of the control equipment in split networks is not known. It is for this reason that the networks produced in this study do not involve stream splitting. In this particular example the consequence of that decision is a penalty of 5% on the network annual cost. This cost penalty has to be weighed against a possible cost of control equipment needed for split networks.

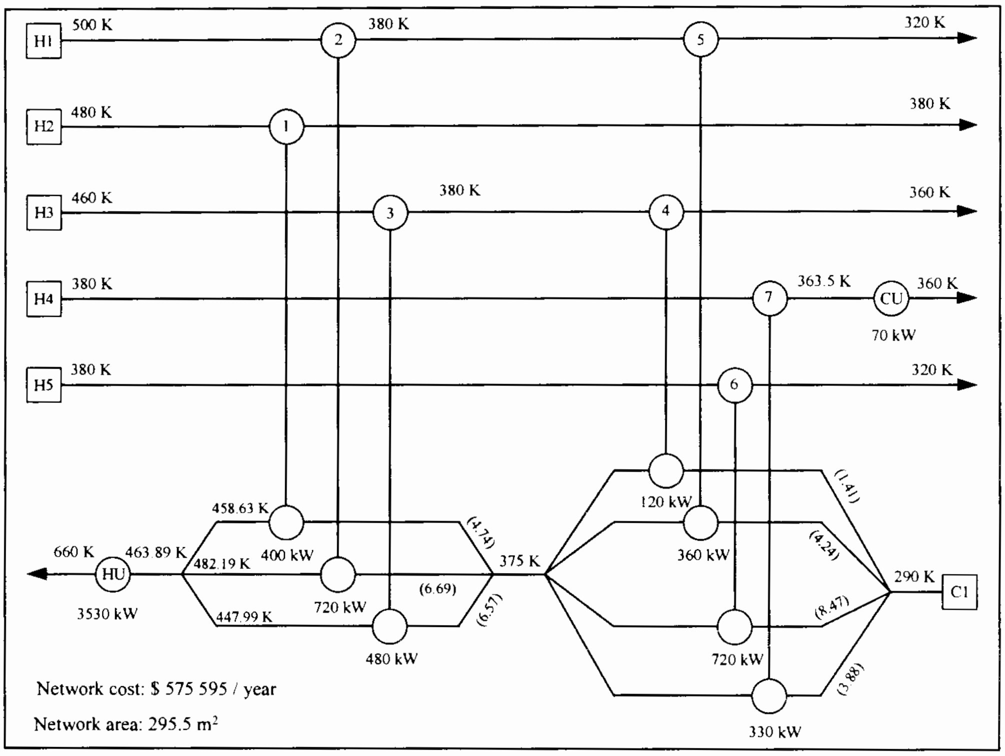

Figure 7.13b: Solution to Problem 13 presented by Yee and Grossmann (1990).

<u>**Problem 14**</u> – 7SP1

This problem involves three hot process streams, four cold process streams, one hot utility, and one cold utility. Masso and Rudd (1969) introduced it. It was solved in this study and the network obtained is shown in Figure 7.14a. Previous solutions are shown in Table 7.8.

Using the stream and cost data provided by Liu (1987) the network annual cost was found to be $30 423/year. The lower cost bound was $22 152/year and the upper cost bound was $307 004/year. The average cost target was $32 161/year. The network performance index was therefore 0.029 and the cost range ratio was 0.83.

All the results listed in Table 7.8 are comparable. The slight differences seen in this table, or any of the other tables in this section, may not always be of concern. To illustrate this point a network design presented by Linnhoff and Flower (1978), shown in Figure 7.14b, is compared with the design obtained in this study, Figure 7.14a.

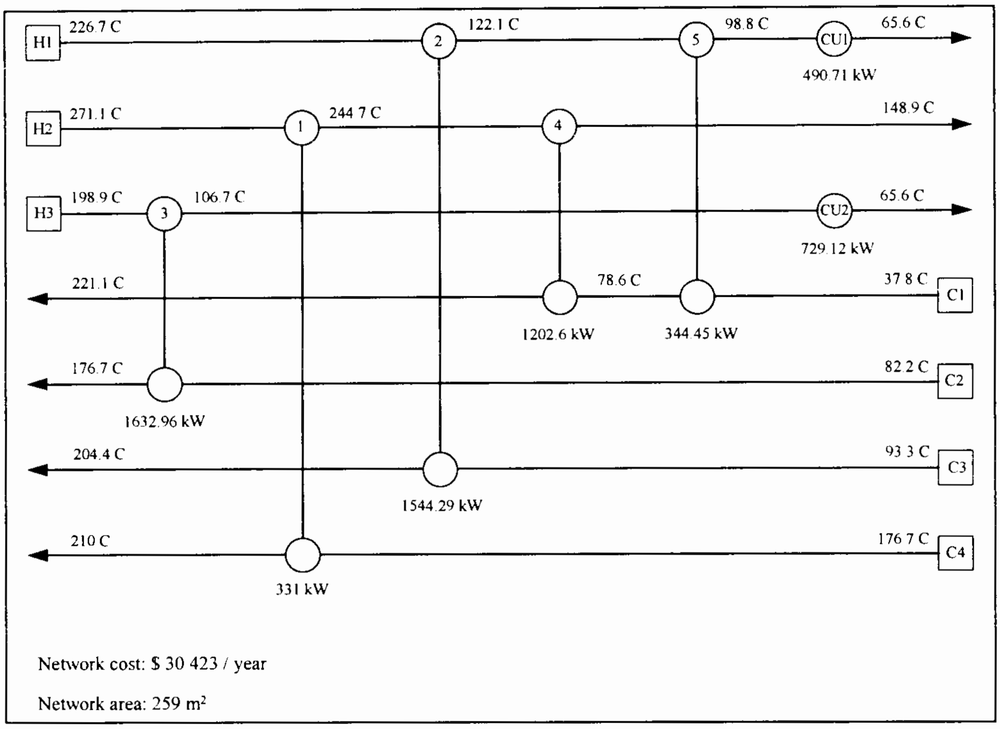

Figure 7.14a: Solution to Case Study Problem 14 (7SP1).

Table 7.8: Solutions to Problem 14 (7SP1) presented by different authors.

Author(s)	Cost, $/yr	NPI	CRR
Masso and Rudd, 1969	34 378	0.043	1.22
Pho and Lapidus, 1973	30 433	0.029	0.83
Ponton and Donaldson, 1974	30 433	0.029	0.83
Linnhoff and Flower, 1978	30 172	0.028	0.80
Grossmann and Sargent, 1978	30 172	0.028	0.80
Su and Motard, 1984	30 172	0.028	0.80
Lee and Reklaitis, 1989	29 839	0.027	0.77
Current study, 1998	30 443	0.029	0.83

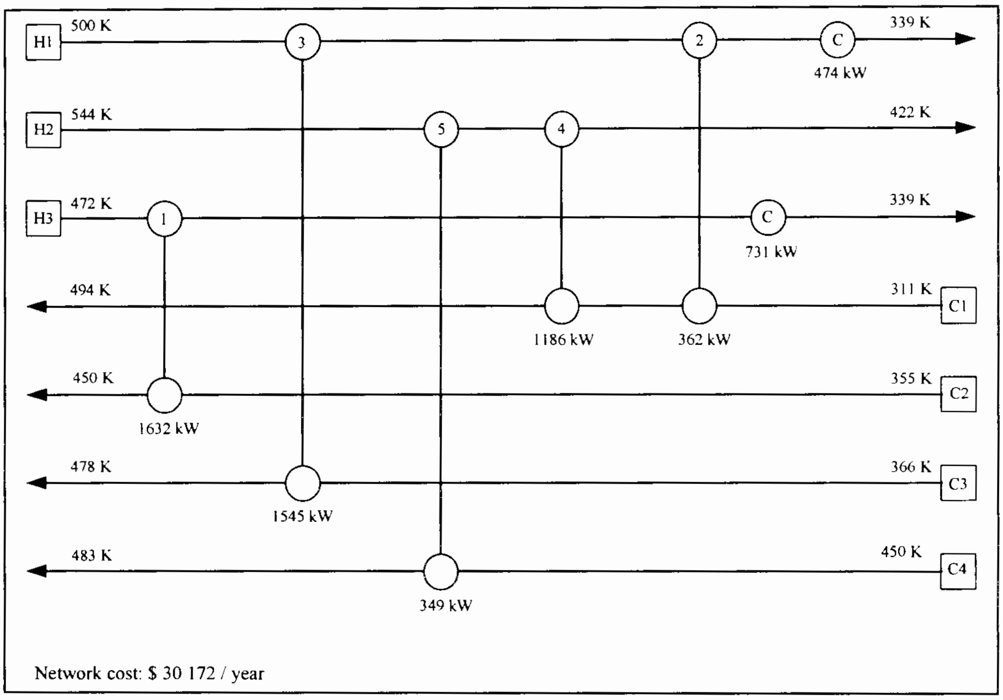

Figure 7.14b: Solution to Problem 14 (7SP1) presented by Linnhoff and Flower (1978).

Figures 7.14a and 7.14b are quite similar in terms of match sequence or structure. The number of units in each of these networks is the same. The two networks have the same match pairs. The only difference between the two structures is the energy distribution among the units. This difference can be attributed to two causes. The first cause is the design technique (Linnhoff and Flower (1978) used the Pinch Design Method). The second cause is the rounding up of figures: Linnhoff and Flower (9178) found the heat load of cold process stream C4 to be 349 kW whereas the heat load of the same stream was calculated in this study to be 331 kW. This small difference (5.4%) can propagate through the network in the sense that the heat loads of other matches, and hence the temperature driving forces, may change. Hence the network annual cost may be affected.

This illustrates the fact that small differences in network annual costs, say 5%, could be associated with some uncertainty and may not always provide conclusive evidence of the performance of a network design.

Problem 15 - 7CIR

This problem involves four hot process streams, three cold process streams, one hot utility, and one cold utility. It was taken from Ciric and Floudas (1991). The network design obtained in this study is shown in Figure 7.15.

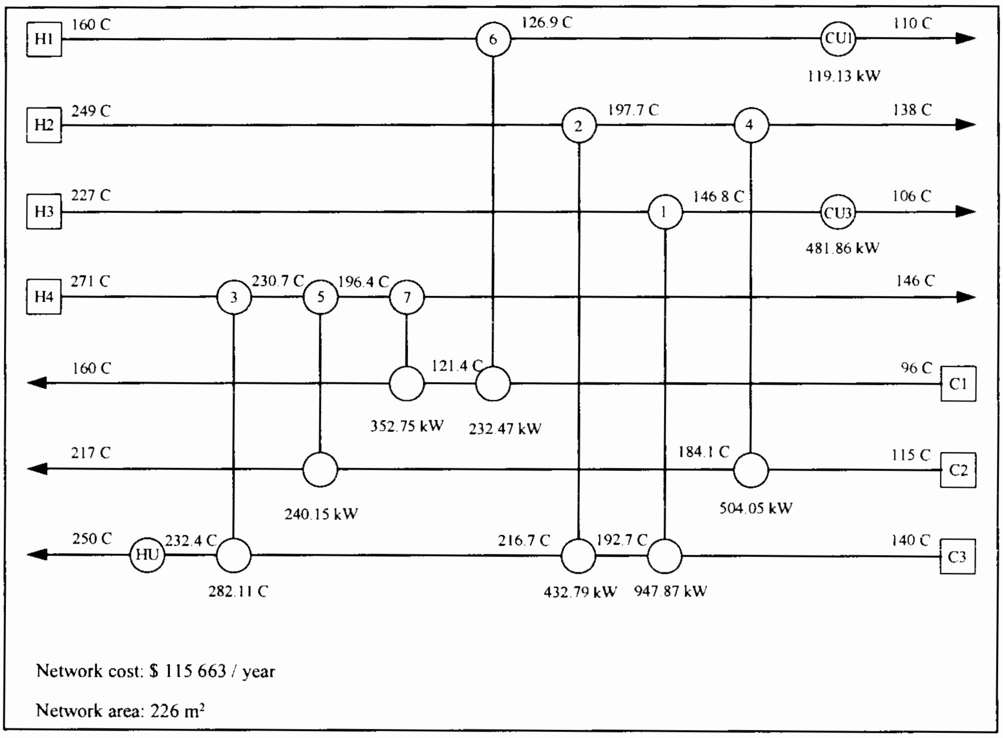

Figure 7.15: Solution to Case Study Problem 15 (7CIR).

The network annual cost was $115 663/year. The lower cost bound was $5 675/year and the upper cost bound was $376 841/year. The average cost target was $74 944/year. Therefore, the network performance index was 0.30 and the cost range ratio was 1.59.

Ciric and Floudas (1990), and Byfield and Ang (1994) solved this problem. Their results are shown in Table 7.9. The networks generated by Ciric and Floudas (1990), and Byfield and Ang (1994) involve stream splitting.

While all the problems discussed so far involved one hot utility and one cold utility, the next two problems involve multiple utilities.

Table 7.9: Solutions to Problem 15 (7CIR) presented by different authors.

Author(s)	Cost, \$/yr	NPI	CRR
Ciric and Floudas, 1990	114 460	0.29	1.57
Byfield and Ang, 1994	106 879	0.27	1.46
Current study, 1998	115 663	0.30	1.59

Problem 16 – 7FRAS1

This problem involves five hot process streams, two cold process streams, three hot utilities, and two cold utilities. The hot utilities are high-pressure steam, intermediate pressure steam, and gas turbine exhaust. The cold utilities are cooling water and chilled water. The presence of these utilities increases the number of match options. The design process becomes a little more complicated because of the combinatorial nature of heat exchanger networks. The solution to this problem is shown in Figure 7.16. The problem was taken from Fraser (1994).

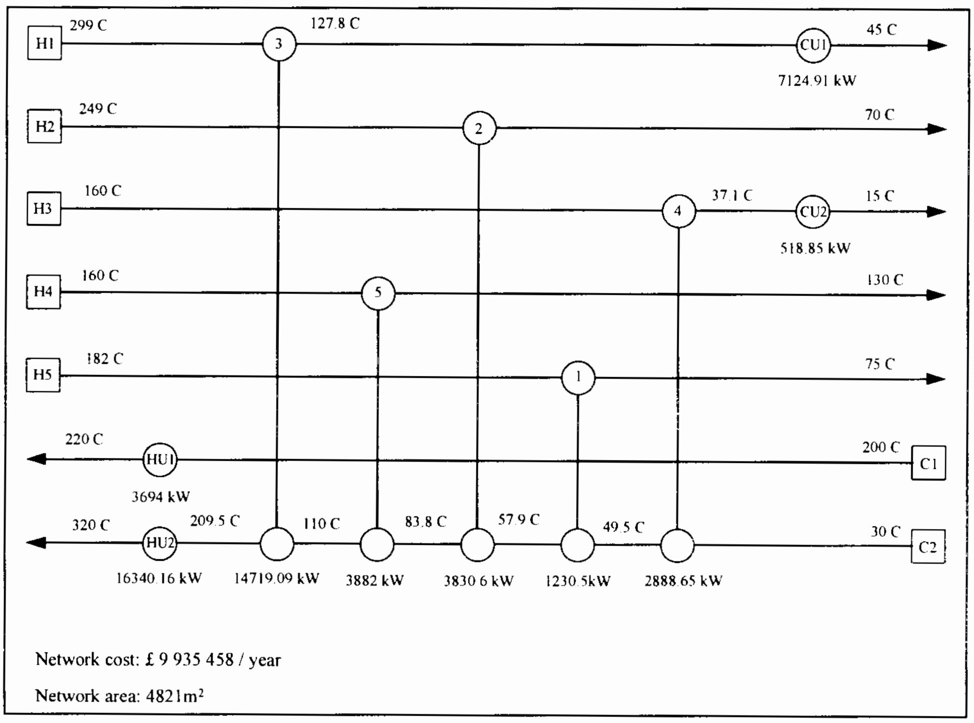

Figure 7.16: Solution to Case Study Problem 16 (7FRAS1).

The presence of many utilities means that the number of ways the process streams can be heated and cooled increases. This situation implies that there is more flexibility in terms of match choices compared to a single utility situation. On one hand a cheap network can be designed if a judicious choice of utilities is made. On the other hand, an expensive network can be designed if the selection of utilities is poor.

The utilities available have different heat transfer properties and have different input and output temperatures. More importantly, their costs are different. The challenge is to find a good balance between process conditions and the cost of utilities, in addition to a proper consideration of process-to-process heat exchange.

The annual cost of the network was found to be £9 935 458/year. The lower cost bound was £243 311/year and the upper cost bound was £25 821 093/year. The average cost target was £13 538 587/year. The network performance index was therefore 0.38 and the cost range ratio was 0.11.

The solution to the problem was not reported in the literature. Fraser (1994) reported the cost target as £1 937 000. The problem involves a linear cost correlation shown in Equation 7.1.

$$Cost = 1\,500\,000 + 142A \qquad (7.1)$$

where A is the heat transfer surface area in m^2. The annual capital recovery factor is 0.6667. In the absence of further information that can be used to assess the result obtained for this problem, a rough estimate of the minimum network annual cost can be determined.

The hot process stream that has the lowest target temperature (15 °C) is H3. There is no cold process stream with a supply temperature that is equal to or lower than 15 °C. Therefore at least one cold utility is required to cool H3 to its target temperature.

The cold process stream that has the highest target temperature (320 °C) is C2. No hot process stream has a supply temperature that is equal to or higher than 320 °C. Therefore at least one cold utility will be required to heat cold process stream C2 to its target temperature.

Since there are five hot process streams and two cold process streams, the network will have at least five process units and two utility units. Assume each unit has a heat transfer surface area that is negligibly small. That is, assume the value of A in Equation 7.1 is zero. Under these conditions the minimum value of the network annual cost would be a product of the number of units (7), the annual capital recovery factor (0.6667) and the first constant in Equation 7.1 (1 500 000). The rough estimate of the minimum annual cost for this network is therefore £7 000 350/year. This annual cost cannot be achieved because it does not involve the heat transfer surface area of the units.

This rough estimate of the network annual cost suggests that the result obtained in this study may be realistic even though it may not be the best design. This example indicates that more attention needs to be focused on the targeting process. Different targeting techniques give different results and there is no evaluation procedure that can be used to confirm the results. Even the same targeting technique may not consistently give realistic results.

Problem 17 - 7FRAS2

This problem is the same as Problem 16 except that the cost correlation is non-linear and that the gas turbine hot utility has been replaced with flue gas. The solution obtained in this study is shown in Figure 7.17.

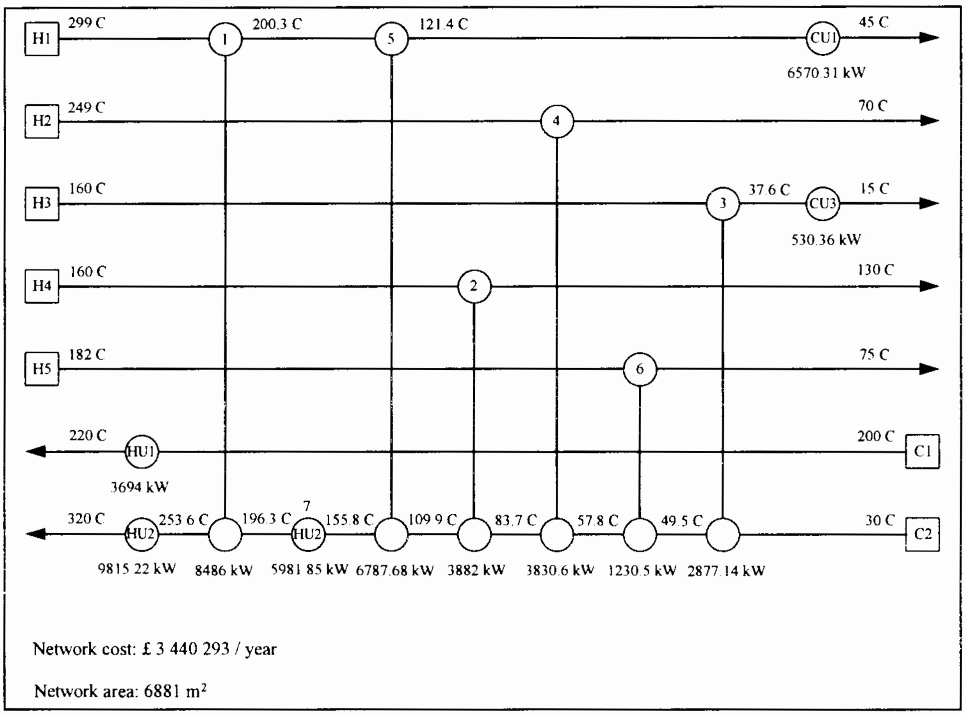

Figure 7.17: Solution to Case Study Problem 17 (7FRAS2).

The network annual cost was found to be £3 440 293/year. The lower cost bound was £2 185 836/year and the upper cost bound was £5 039 515/year. The average cost target was £2 382 181/year. The network performance index was therefore 0.44 and the cost range ratio was 6.39.

Solutions to the problem were not found in the literature. Fraser (1994) provided a cost target of £3 257 000. This cost target (presumably annualised) is 37% higher than that found in this study. The network annual cost obtained in this study is higher than both of these cost targets are.

Although there is no indication of reasonable solutions to Problems 16 and 17 it was obvious that the need for evaluation of targeting results cannot be over-emphasised if design targets are to be meaningful.

Problem 18 - 7YEE

This problem involves three hot process streams, four cold process streams, one hot utility, and one cold utility. The streams have significantly different heat transfer coefficients. The problem was taken from Yee and Grossmann (1990). Colberg and Morari (1990) previously discussed it. The solution obtained in this study is shown in Figure 7.18a.

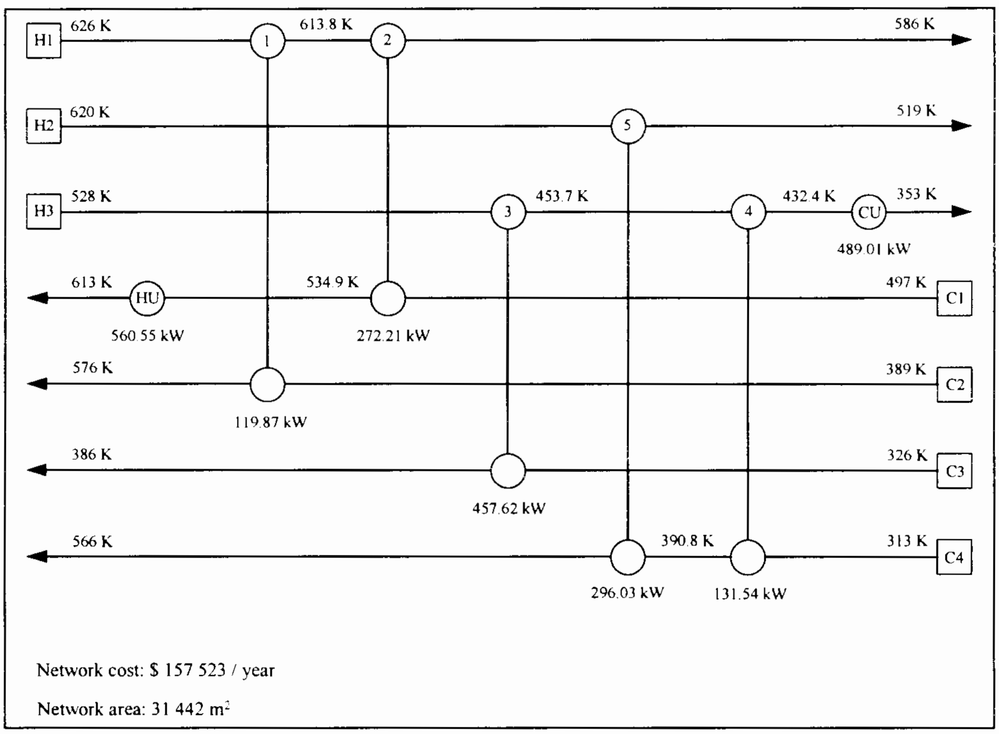

Figure 7.18a: Solution to Case Study Problem 18 (7YEE).

The cost of the hot utility was assumed to be \$80/kW, and the cost of the cold utility was assumed to be \$20/kW. Yee and Grossmann (1990), and Colberg and Morari (1990) did not specify the cost of utilities. The network cost was found to be \$157 523. The lower cost bound was \$10 014 and the upper cost bound was \$267 936. The average cost target was \$154 897. The network performance index was 0.57 and the cost range ratio was 1.02. Previous solutions to the problem can be used to get an indication as to how good or bad the result is.

The solutions obtained from the literature involved only the capital cost. The capital cost of the network designed by Colberg and Morari (1990) was taken from Yee and Grossmann (1990). The total costs of the networks were calculated in this study on the basis of values assumed for the cost of utilities. The cost of utilities was added to the capital costs reported by Yee and Grossmann (1990). The results are shown in Table 7.10.

The results shown in Table 7.10 indicate that the result obtained in this study is comparable to the results reported in the literature. However, there is no conclusive evidence that the network design is near optimal.

Table 7.10: Solutions to Problem 18 (7YEE) presented by different authors.

Author(s)	Cost, \$/yr		NPI	CRR
	Capital	Total		
Colberg and Morari (1990)	177 385	200 373	0.74	1.31
Yee and Grossmann (1990)	150 998	173 978	0.64	1.13
Current study, 1998	102 898	157 523	0.57	1.02

Since the cost of utilities was not specified in the original problem it is advisable to examine its effect on the total network cost of the fixed designs whose costs are shown in Table 7.10. Increasing the cost of the hot utility by \$40/kW from \$40/kW to \$840/kW and the cost of the cold utility by \$10/kW from \$10/kW to \$210/kW does this. At each interval the total cost of utilities was added to the fixed capital cost reported in Table 7.10. The variation of the cost for each of the designs whose costs are shown in Table 7.10 is shown in Figure 7.18b.

In Figure 7.18b the symbols CM, YG, and CS indicate the workers who presented the solutions shown in Table 7.10, namely, Colberg and Morari (1990), Yee and Grossmann (1990), and the current study, respectively.

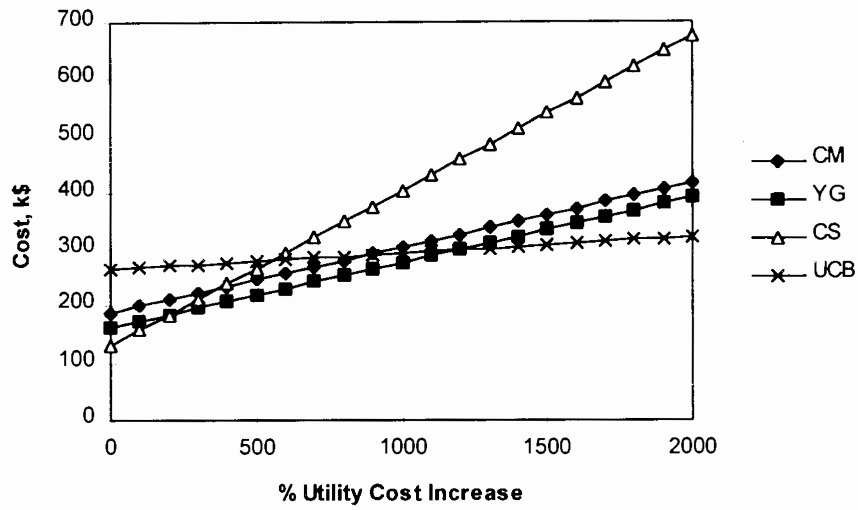

Figure 7.18b: Variation of the total network cost and the upper cost bound with the cost of utilities.

For this particular problem, it can be seen that if the cost of utilities rises to a certain value each of the designs will have a total cost that exceeds the upper cost bound. The behaviour of these networks as the cost of utilities increases is related to the minimum utility requirements. If the amount of minimum utilities required is small, the upper cost bound is less sensitive to changes in the cost of utilities. Likewise, if the amount of utilities consumed by a network is small, the network cost will be less sensitive to changes in the cost of utilities.

For this example, as for Problem 6, there is a range of values of the cost of utilities in which it is economical to operate a network design. It would not be economical to operate the design presented in this study if the cost of the hot utility is more than \$280/kW and the cost of the cold utility is more than \$70/kW. For the design presented by Colberg and Morari (1990) it would not be economical to operate at a cost of the hot utility that is higher than \$400/kW and a cost of the cold utility that is higher than \$100/kW. For the design presented by Yee and Grossmann (1990) it would not be economical to operate at a cost of the hot utility that is higher than \$520/kW and a cost of the cold utility that is higher than \$130/kW.

A deduction that can be made in this example is that there is an optimum design for each utility cost. Since the cost of utilities generally increases with time it would be advisable to examine the range of utility costs in which economic operation of a network can be achieved.

<u>Problem 19</u> – 9LIN

This problem was taken from Linnhoff and Ahmad (1990). It involves four hot process streams, five cold process streams, one hot utility, and one cold utility. The solution obtained in this study is shown in Figure 7.19.

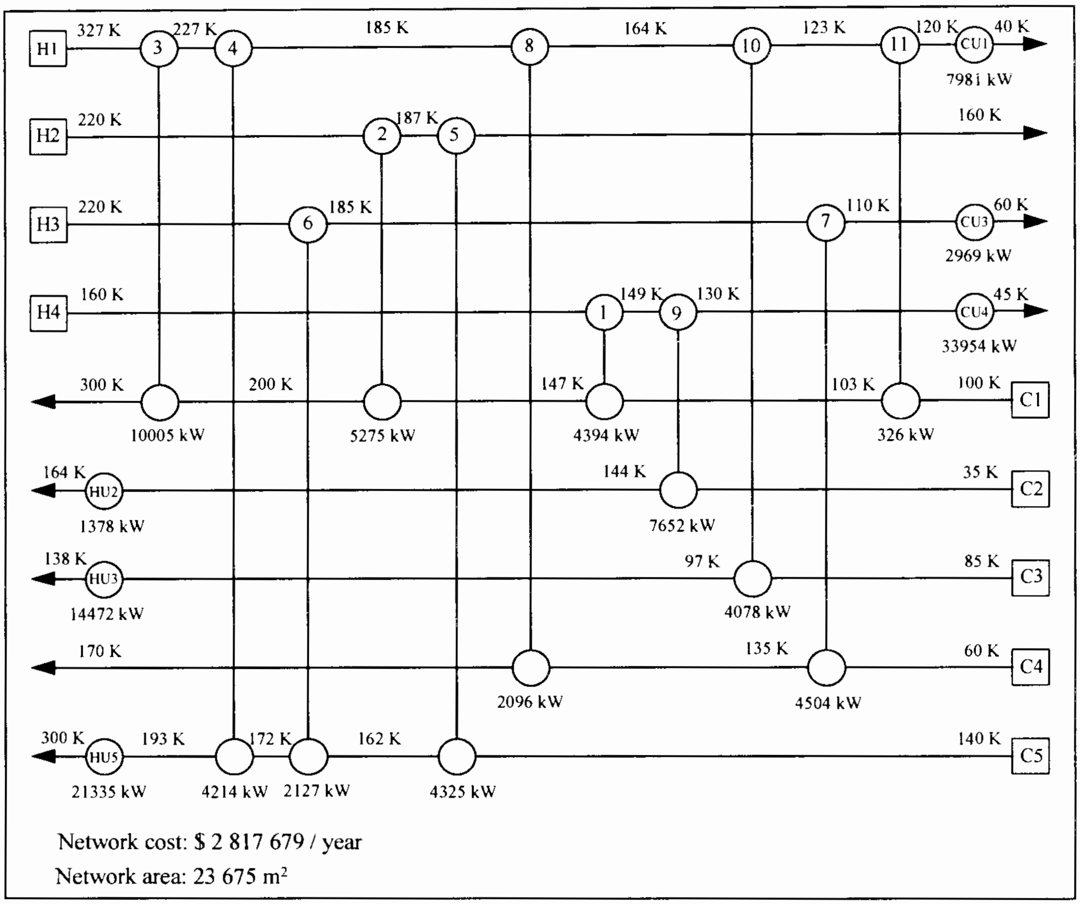

Figure 7.19: Solution to Case Study Problem 19 (9LIN).

The network annual cost was found to be \$2 817 679/year. The lower cost bound was \$46 320/year and the upper cost bound was \$6 393 408/year. The average cost target was \$1 182 014/year. The network performance index was therefore 0.44 and the cost range ratio was 2.44.

Linnhoff and Ahmad (1990), and Zhu et al. (1995) also solved the same problem. The results are shown in Table 7.11. The results shown in Table 7.11 are comparable. The maximum percentage difference between any two annual costs in the table is 6%. An interesting observation made in this study is that the network design presented by Linnhoff and Ahmad (1990) has 13 units; the design presented by Zhu et al. (1995) has 10 units; and the design obtained in this work has 17 units. It seems there is no obvious or simple correlation between the cost of a network and the number of units.

Table 7.11: Solutions to Problem 19 (9LIN) presented by different authors.

Author(s)	Cost, $/yr	NPI	CRR
Linnhoff and Ahmad (1990)	2 890 000	0.45	2.50
Zhu et al. (1995)	2 980 000	0.46	2.58
Current study, 1998	2 817 679	0.44	2.44

<u>**Problem 20**</u> – 9AHM

This problem was taken from Ahmad et al. (1990). It involves five hot process streams, four cold process streams, one hot utility, and one cold utility. The main feature of this problem is that there are special requirements for materials of construction on certain streams. Two process streams require stainless steel, two more streams require titanium, and the rest of the streams can be accommodated in carbon-steel. The solution obtained in this study is shown in Figure 7.20.

The network annual cost was found to be $1 886 900/year. The lower cost bound was $767 250/year and the upper cost bound was $2 920 942/year. The average cost target was $2 008 528/year. Therefore, the network performance index was 0.52 and the cost range ratio was 0.90.

Ahmad et al. (1990) provided a solution for this problem. The annual cost of the network is shown in Table 7.12. The solutions shown in Table 7.12 are comparable. The network obtained in this study is about 3% more expensive than the split network presented by Ahmad et al. (1990).

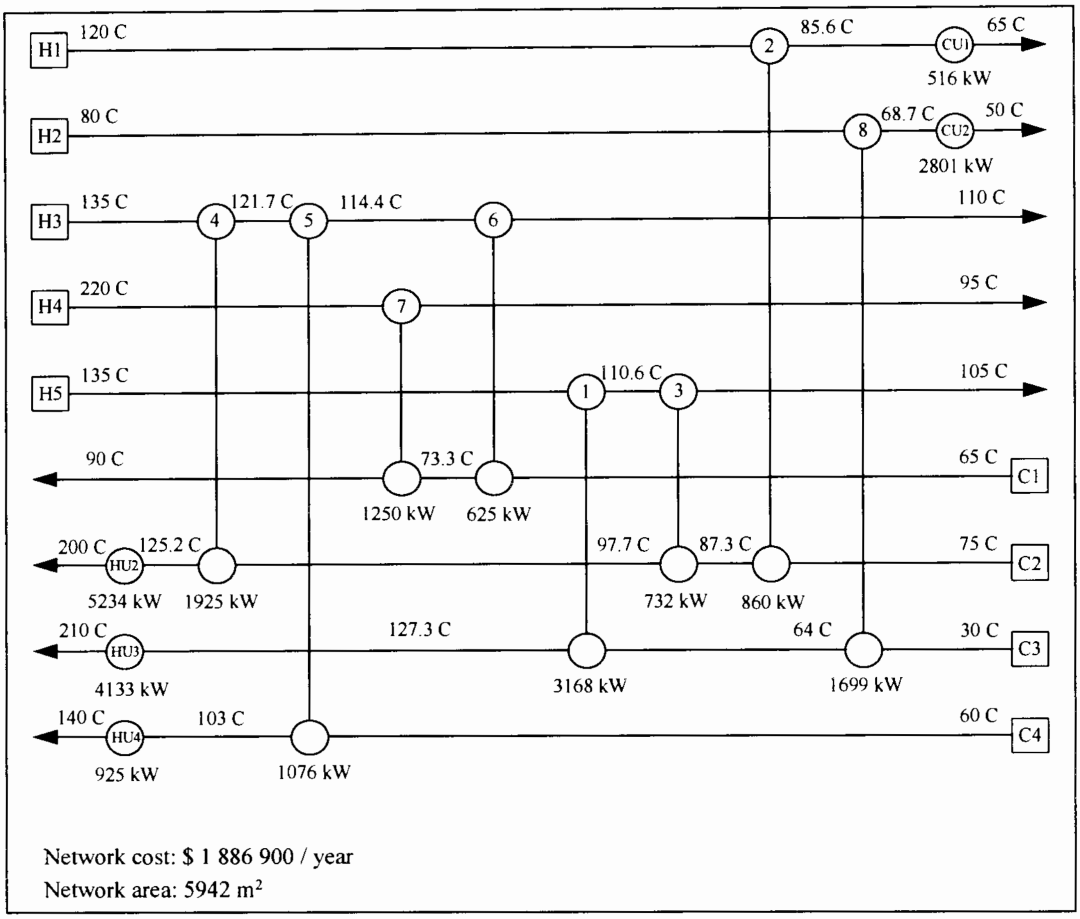

Figure 7.20: Solution to Case Study Problem 20 (9AHM).

Table 7.12: Solution to Problem 20 (9AHM) presented by Ahmad et al. (1990).

Author(s)	Cost, $/yr	NPI	CRR
Ahmad et al. (1990)	1 834 000	0.50	0.86
Current study, 1998	1 886 900	0.52	0.90

Problem 21 - 9JEG

This problem was taken from Jegede and Polley (1992). It involves four hot process streams, five cold process streams, one hot utility, and one cold utility. There are different materials of construction for the exchangers and the heat transfer coefficients of the streams are match-dependent. The solution obtained in this work is shown in Figure 7.21.

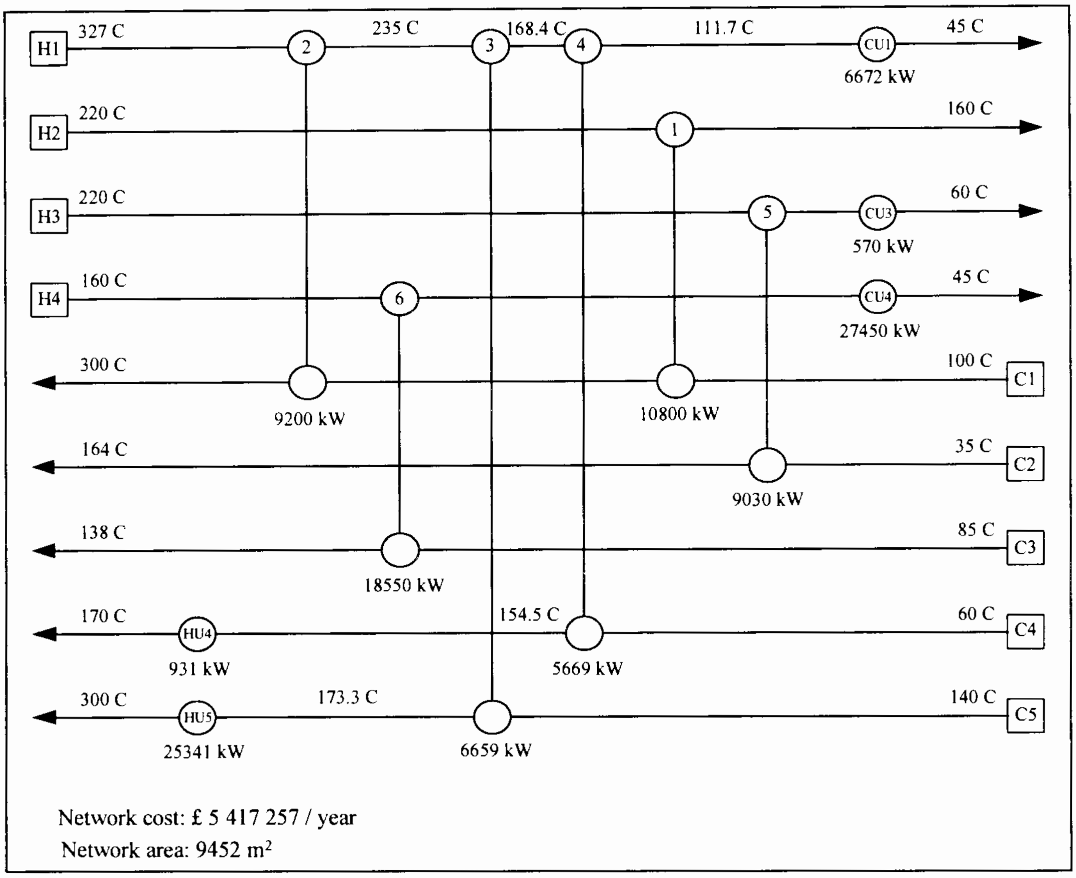

Figure 7.21: Solution to Case Study Problem 21 (9JEG).

The network annual cost was £5 417 257/year. The lower cost bound was £84 200/year and the upper cost bound was £10 898 354/year. The average cost target was £2 576 772/year. Thus, the network performance index was 0.49 and the cost range ratio was 2.14. The network annual cost reported by Jegede and Polley (1992) is shown in Table 7.13.

Table 7.13: Solution to Problem 21 (9JEG) presented by Jegede and Polley (1992).

Author(s)	Cost, £/yr	NPI	CRR
Jegede and Polley (1992)	5 550 300	0.51	2.19
Current study, 1998	5 417 257	0.49	2.14

The results shown in Table 7.13 are comparable. This means that the result obtained in this study is a reasonable solution. The cost target found by Jegede and Polley (1992) was

£5 739 200/year, and is twice the value of the average cost target found in this study. The question to be answered is which of the targets is closer to the actual optimum solution.

Problem 22 - 10BYF

This problem was taken from Byfield and Ang (1994). It involves five hot process streams, five cold process streams, one hot utility, and one cold utility. The solution obtained in this study is shown in Figure 7.22.

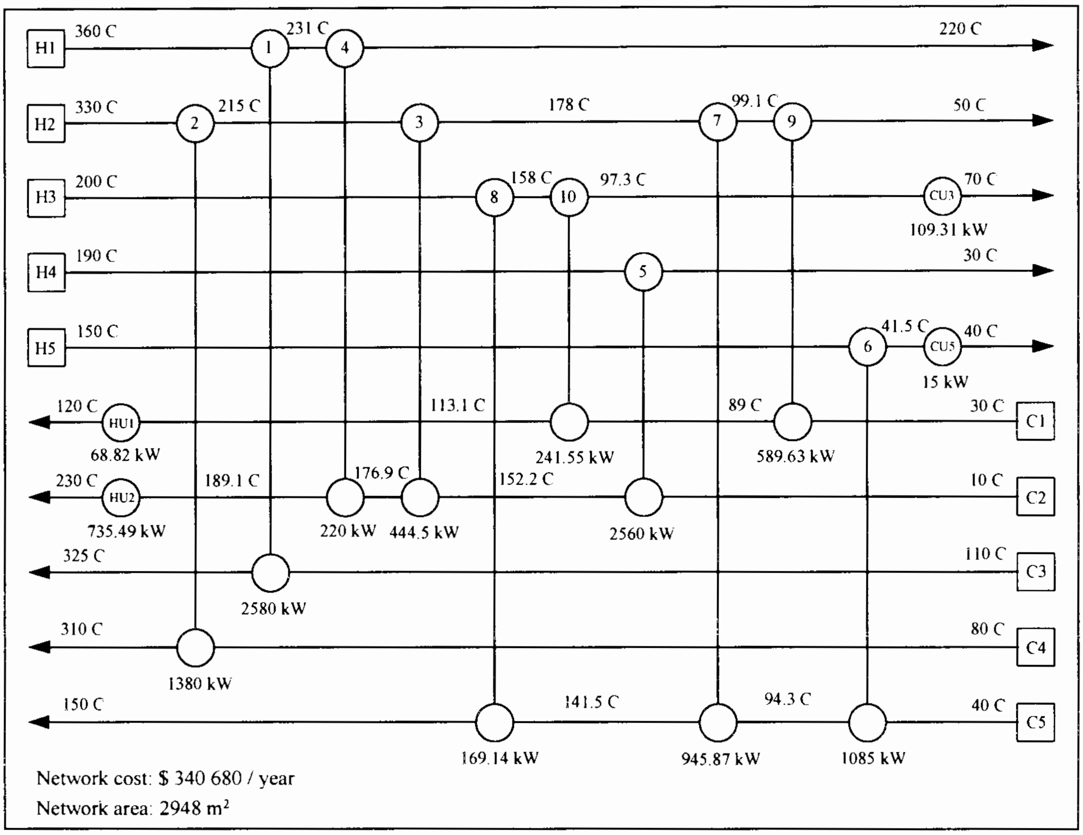

Figure 7.22: Solution to Case Study Problem 22 (10BYF).

The annual cost of the network was found to be \$340 680/year. The lower cost bound was \$68 000/year and the upper cost bound was \$1 436 335/year. The average cost target was \$330 811/year. The network performance index was 0.20 and the cost range ratio was 1.04.

The network annual cost found by Byfield and Ang (1994) is shown in Table 7.14. The values of the annual cost are comparable.

Table 7.14: Solution to Problem 22 (10BYF) presented by Byfield and Ang (1994).

Author(s)	Cost, £/yr	NPI	CRR
Byfield and Ang (1994)	387 350	0.23	1.22
Current study, 1998	340 680	0.20	1.04

Problem 23 - 10SP1

This problem was taken from Liu (1987). Pho and Lapidus (1973) initially discussed it. It involves five hot process streams, five cold process streams, one hot utility, and one cold utility. The solution obtained in this study is shown in Figure 7.23.

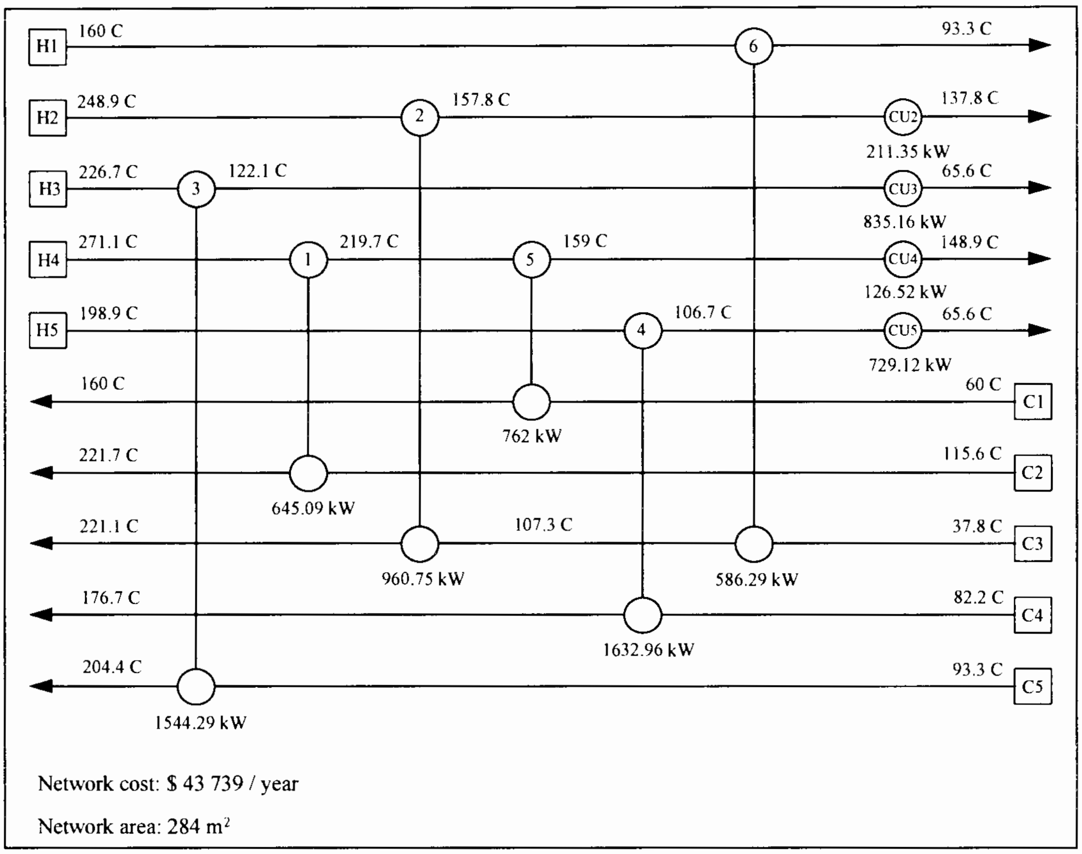

Figure 7.23: Solution to Case Study Problem 23 (10SP1).

The network annual cost was $43 739/year. The lower cost bound was $34 048/year and the upper cost bound was $385 669/year. The average cost target was $45 944/year. The network performance index was found to be 0.028 and the cost range ratio was 0.81. Some of the annual costs reported for this problem are shown in Table 7.15.

Table 7.15: Solutions to Problem 23 (10SP1) presented by different authors.

Author(s)	Cost, $/yr	NPI	CRR
Pho and Lapidus, 1973	44 158	0.029	0.85
Ponton and Donaldson, 1974	44 160	0.029	0.85
Nishida et al. (1977)	43 984	0.028	0.84
Linnhoff and Flower, 1978	43 934	0.028	0.83
Grossmann and Sargent, 1978	44 160	0.029	0.85
Boland and Linnhoff, (1979)	43 857	0.028	0.82
Su and Motard, 1984	43 857	0.028	0.82
Lee and Reklaitis, 1989	43 856	0.028	0.82
Yee et al. (1990)	43 878	0.028	0.83
Current study, 1998	43 739	0.028	0.81

All the results shown in Table 7.15 are comparable. From the results presented in this table it may be speculated that the global optimum for this problem is in the range of $43 000/year to $44 000/year.

The overall evaluation of the technique developed in this study is presented in the next section.

7.2 Overall Results

In this section the results obtained by the new method are listed alongside the best results obtained from the literature. The list of investigators who presented the cheapest networks for the case study problems is given in Table 7.16. The first column in the table shows the identity of the network problem. The workers who provided the best solution reported in the literature are listed in the second column. The different techniques used by these investigators to solve the problems are shown in the third column of the table.

Table 7.16: Sources of the solutions to the case study problems

Problem	Investigator(s)	Design method
3NIS	Nishida et al., 1977	Algorithmic-Evolutionary Approach
4SP1	Grossmann and Sargent, 1978	Mixed Integer Non-linear Programming
4SP2	Grimes et al., 1982	Algorithmic-Evolutionary procedure
4TC2	Lee and Reklaitis, 1989	Algorithmic-Evolutionary procedure
4YEE1	Yee and Grossmann, 1990	Mixed Integer Non-linear Programming
4YEE3	Byfield and Ang, 1994	Simulated Annealing
5SP1	Pho and Lapidus, 1973	Tree Searching Algorithm
5ZHU	Zhu et al., 1995	"Block Decomposition"
6SP1	Su and Motard, 1984	Evolutionary Development
6YEE	Yee and Grossmann, 1990	Mixed Integer Non-linear Programming
7SP1	Lee and Reklaitis, 1989	Algorithmic-Evolutionary Procedure
7CIR	Byfield and Ang, 1994	Simulated Annealing
7YEE	Yee and Grossmann, 1990	Mixed Integer Non-linear Programming
9LIN	Linnhoff and Ahmad, 1990	Pinch Analysis
9AHM	Ahmad et al., 1990	Pinch Analysis
9JEG	Jegede and Polley, 1992	Pinch Analysis
10BYF	Byfield and Ang, 1994	Simulated Annealing
10SP1	Lee and Reklaitis, 1989	Algorithmic-Evolutionary Procedure

The solutions to the problems are presented in Table 7.17. The second and third columns show the lower and upper cost bounds, respectively. The fourth column shows the average cost target (ACT). The best solutions to the problems reported in the available literature are listed in the fifth column. The final solutions obtained in this study are given in the sixth column. The percentage difference between the results obtained in this study and those reported in the literature are listed in the seventh column. Each entry in this column was obtained by subtracting the annual cost reported in the literature from that obtained in this study, dividing the difference by the annual cost reported in the literature, and multiplying this result by one hundred. The percentage cost savings were calculated by subtracting the network performance index from one and multiplying this difference by a hundred.

Problems in which the currency used was pounds instead of dollars are indicated with an asterisk (*) in the first column of Table 7.17. These are problems 7FRAS2 and 9JEG. Problems for which the network annual cost was not reported in the literature have blank cells that contain a dash. These problems are 3SP1, 4YEE2, 4FRAS, 7FRAS1, and 7FRAS2. Problems whose costs were not annualised are indicated with two asterisks (**) in the first column. These problems are 4YEE1 and 7YEE.

Table 7.17: Results obtained by the new network design technique compared with the best results from the literature.

Problem	Cost Bounds, $/year		ACT, $/year	Network cost, $/year		Percentage	
	Lower	Upper		Literature	Current	Difference	Savings
3SP1	65	26 533	877	-	1 050	-	96.00
3NIS	0	166 028	1 328	1 475	384	-74.00	99.77
4SP1	7 496	105 227	13 164	10 592	10 599	0.07	97.00
4SP2	12 552	400 219	26 143	19 141	21 144	10.46	94.72
4TC2	2 194	86 823	5 713	16 173	14 516	-10.25	97.80
4YEE1**	54 000	795 773	561 433	809 970	751 187	-7.26	6.00
4YEE2	36 200	133 476	53 590	-	77 803	-	57.00
4YEE3	8 000	521 609	88 095	79 429	79 872	0.56	86.00
4FRAS	8 913	72 004	19 716	-	35 540	-	58.00
5SP1	33 368	260 264	40 333	38 268	38 964	1.82	97.53
5ZHU	2 295	72 736	67 443	54 131	56 443	4.27	26.41
6SP1	27 760	294 190	33 865	35 010	35 005	-0.01	97.30
6YEE**	484 400	1 007 539	544 481	575 595	605 263	5.15	77.00
7SP1	22 152	307 004	32 161	29 839	30 423	1.96	97.10
7CIR	5 675	376 841	74 944	106 879	115 663	8.22	70.00
7FRAS1	243 311	25 821 093	13 538 587	-	9 935 458	-	62.00
7FRAS2*	2 185 836	5 039 515	2 382 181	-	3 440 293	-	56.00
7YEE	10 014	267 936	154 897	150 998	157 523	4.32	43.00
9ZHU	46 320	6 393 408	1 182 014	2 890 000	2 817 679	-2.50	56.00
9AHM	767 250	2 920 942	2 008 528	1 834 000	1 886 900	2.88	48.00
9JEG*	84 200	10 898 354	2 576 772	5 550 300	5 417 257	-2.40	51.00
10BYF	68 000	1 436 335	330 811	387 350	340 680	-12.05	80.00
10SP1	34 048	385 669	45 944	43 856	43 739	-0.27	97.20

7.3 Discussion

The purpose of this evaluation process is to determine if the new technique can consistently generate near-optimal networks. If networks that are near optimal can be generated consistently then further studies can be done to handle unresolved network design issues. Examples of unresolved issues in network design are global optimality, controllability, resilience, and specification of a minimum approach temperature or minimum flux.

The comparison of results obtained by the new technique with the best solutions reported in the literature gives an indication of the consistency and accuracy of the new technique.

In Section 7.3.1 the results obtained in this study are compared to the best results reported in the literature. The significance of cost targeting in network evaluation is examined in Section 7.3.2. The significance of evolutionary development is discussed in Section 7.3.3. Section 7.3.4 highlights the effects of stream splitting, minimum utility requirements, and the minimum number of units on network optimality. The significance of the technique is discussed in Section 7.3.5. The weaknesses of the technique are presented in Section 7.3.6.

7.3.1 **Comparison of the Results with those Reported in the Literature**

The overall performance of the new technique is summarised in Table 7.17. The lower and upper cost bounds provide a consistent and reproducible set of reference points for each problem. These cost limits are determined by the stream and cost data defining the problem in question. All the results obtained in this study were within the respective cost limits as expected.

Network design results reported in the literature prove to be useful reference points for network evaluation. To a certain extent they show the designer what can or cannot be achieved, and they promote a sense of competition. It will be noted, though, that they are not perfect references for network evaluation because it is not known how far they are from the global optima. Furthermore, the design solutions to other problems may not be available in the literature.

The worst solution obtained in this study (4SP2) was about 10.5% higher than the result reported in the literature. This solution was discussed earlier in this chapter (Problem 4 in Section 7.1). The performance of the technique against the other literature techniques can better be illustrated by plotting the percentage difference shown in Table 7.17 as shown in Figure 7.24.

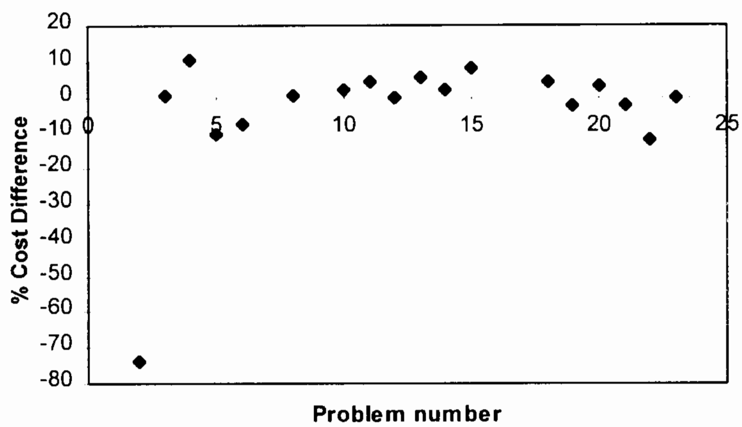

Figure 7.24: Percent cost difference between solutions generated in this study and those reported in the literature.

For perfect performance the points shown in Figure 7.24 should lie on or below the horizontal axis. Only 12 out of the 18 points (67%) are on or below the x-axis. Given the variations in solution conditions this is a reasonably good performance. Seventeen out of the eighteen solutions (94%) are within 10% of the best results reported in the literature. No solutions were reported in the literature for five of the 23 problems.

7.3.2 The Significance of Cost Targets

In general, targets are intended to guide the design process from a state in which there are many possible outcomes to a state in which the best outcome possible is identified. By the best outcome possible is meant a design that can be improved to a near optimal structure. In this section the significance of network design targets in network evaluation is examined. The network cost limits introduced in this study and cost targets are briefly discussed in Sections 7.3.2.1 and 7.3.2.2, respectively.

7.3.2.1 Network Cost Limits

In this study network cost limits were defined in order to restrict network costs within a certain cost range that is derived from the stream and cost data defining the problem at hand. The significance of these cost limits is that network costs as well as cost targets should be within these bounds in order to be economically meaningful.

Both the cost targets and the network costs should be as close as possible to the lower cost bound in order to be as close as possible to the global optimum. If this condition holds for the network cost then the network is at least near optimal. The major difficulty is defining "as close as possible to the lower cost bound." This difficulty arises from the fact that there is no single or fixed value of the deviation from the lower cost bound that can define "near optimality" for all network design situations. This is due to the fact that the maximum cost savings for each problem is defined by the stream and cost data defining the particular problem. This situation can be illustrated by tabulating the network performance index, cost range ratio, network cost, and the result obtained from the literature, as shown in Table 7.18.

A network performance index that is as close as possible to zero is desirable because it indicates a maximum cost saving. On the other hand, a network performance index that is close to but not greater than one does not necessarily imply a poor cost saving. In fact it can correspond to the maximum cost saving possible.

A cost range ratio that is less than or equal to one is desirable because it indicates that the design is on target. On the other hand, a cost range ratio that is larger than one does not necessarily imply a poor design. The reason for this is that an average cost target may be too small to be realistic and this is not always obvious.

Table 7.18 shows that there is no relation between the network performance index and the cost range ratio. It can also be seen that there is no relation between the network cost and either the network performance index or the cost range ratio. These observations imply that neither the network performance index nor the cost range ratio can be used as a consistent criterion for network evaluation.

Table 7.18: Relation between the network cost limits and the network cost.

Problem	Network cost, $/year		ACT, $/year	Cost Ratio		Percentage	
	Literature	Current		NPI	CRR	Difference	Savings
3SP1	-	1 050	877	0.04	1.21	-	96.00
3NIS	1 475	384	1 328	0.0023	0.29	-74.00	99.77
4SP1	10 592	10 599	13 164	0.03	0.55	0.07	97.00
4SP2	19 141	21 144	26 143	0.022	0.63	10.46	94.72
4TC2	16 173	14 516	5 713	0.19	4.57	-10.25	97.80
4YEE1**	809 970	751 187	561 433	0.94	1.37	-7.26	6.00
4YEE2	-	77 803	53 590	0.43	2.39	-	57.00
4YEE3	79 429	79 872	88 095	0.14	0.897	0.56	86.00
4FRAS	-	35 540	19 716	0.42	2.46	-	58.00
5SP1	38 268	38 964	40 333	0.025	0.80	1.82	97.53
5ZHU	54 131	56 443	67 443	0.74	0.80	4.27	26.00
6SP1	35 010	35 005	33 865	0.027	1.19	-0.01	97.30
6YEE**	575 595	605 263	544 481	0.23	2.01	5.15	77.00
7SP1	29 839	30 423	32 161	0.029	0.83	1.96	97.10
7CIR	106 879	115 663	74 944	0.30	1.59	8.22	70.00
7FRAS1	-	9 935 458	13 538 587	0.38	0.11	-	62.00
7FRAS2*	-	3 440 293	2 382 181	0.44	6.39	-	56.00
7YEE	150 998	157 523	154 897	0.57	1.02	4.32	43.00
9ZHU	2 890 000	2 817 679	1 182 014	0.44	2.44	-2.50	56.00
9AHM	1 834 000	1 886 900	2 008 528	0.52	0.90	2.88	48.00
9JEG*	5 550 300	5 417 257	2 576 772	0.49	2.14	-2.40	51.00
10BYF	387 350	340 680	330 811	0.20	1.04	-12.05	80.00
10SP1	43 856	43 739	45 944	0.028	0.81	-0.27	97.20

In the following section the use of network design targets in network evaluation is briefly discussed. The question to be answered is whether or not cost targets can be used to evaluate network designs. Cost targets obtained in three ways will be used to find an answer to this question. Firstly, the average cost target was determined for each of the case study problems. Secondly, for some of the case study problems the cost targets were obtained from the literature. Thirdly, for some problems a computer program, UCTNET, developed by Gillespie and Fraser (1989) was used to determine the cost targets.

7.3.2.2 Network Cost Targets

In this section the network costs are compared to the network cost targets. For each problem two network costs are examined, where possible. The first network cost is the result found in this study by the new technique. The second network cost is the result reported in the literature.

Cost targets obtained in three different ways mentioned at the end of the last section are used to evaluate the network designs, where possible. The cost targets obtained from the literature and those targets that were determined using UCTNET were compared to the corresponding average cost targets.

Since the costs of the different case study problems differ widely, it was convenient to use a ratio of one cost to another cost (network cost to cost target, or cost target to cost target), the cost ratio. The comparison between the network cost and the cost target is made by taking the ratio of the network cost to the cost target. If the ratio is one then the network cost is equal to the cost target. If the ratio is greater than one then the network cost is larger than the cost target. If the ratio is less than one then the network cost is less than the cost target.

Thus different network costs can be compared to the same cost target. Furthermore, cost ratios can be used to compare different network costs to one another. If the ratio involving one network cost is higher than the corresponding ratio involving another network cost then the former network cost is higher than the latter network cost.

*7.3.2.2.1 **Comparison of the Network Cost to the Average Cost Target***

Using the results shown in Table 7.18 the network cost (NC) obtained by the new technique, and the network cost reported in the literature (LNC) were compared to the average cost target. The results are shown in Figure 7.25.

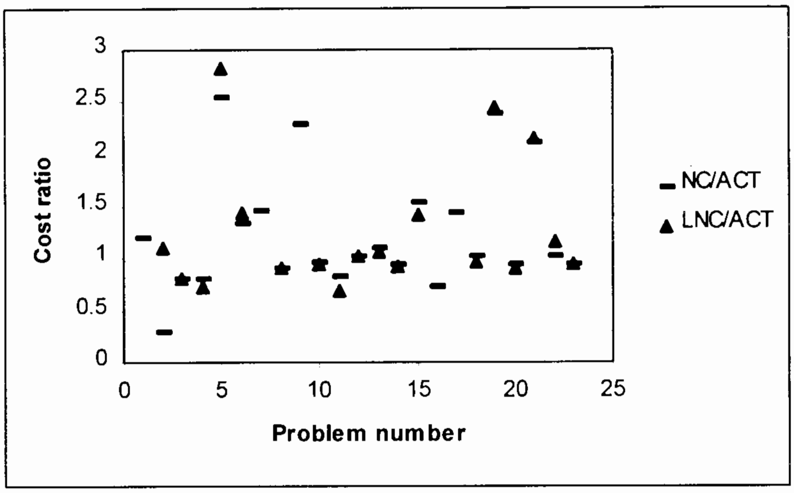

Figure 7.25: Comparison of the network cost to the average cost target.

In Figure 7.25 it can be seen that the cost of some network designs generated by the new technique were close to the average cost target since their cost ratios were close to one. For other network designs the cost was as high as two and half times the average cost target. For the rest of the network designs generated by the new technique the network cost was lower than the average cost target.

Similar trends were observed when the network costs reported in the literature were compared to the average cost target. It can also be seen that the cost ratios of some network designs generated in this study were very close to those of networks reported in the literature. The scatter of the points between the cost ratios of 0 and 3 shows that, generally, it was not easy to achieve the average cost target.

Ideally, all the points in Figure 7.25 would be expected to lie on the horizontal axis at a cost ratio of one. This would be a condition in which the network costs generated by the new technique and those reported in the literature are equal to each other and to the average cost targets.

7.3.2.2.2 Comparison of the Network Cost to the Cost Target Reported in the Literature.

For ten out of the twenty-three problems studied in this work cost targets were reported in the literature. These problems and cost targets are shown in Table 7.19.

Table 7.19: Cost targets for some of the case study problems.

Problem	Author(s)	HRAT	Cost Target
4YEE1	Colberg and Morari, 1990	20°C	$714 000
4YEE2	Yee et al., 1990	13 K#	$79 850/year
4YEE3	Zhu et al., 1995	20°C	$77 017/year
4FRAS	Fraser, 1994	15°C	$45 296/year
5ZHU	Zhu et al., 1995A	30 K	$48 975/year
7FRAS1	Fraser, 1994	20°C	£1 937 000
7FRAS2	Fraser, 1994	12°C	£3 257 000
9LIN	Linnhoff and Ahmad, 1990	26°C	$2 890 000/year
9AHM	Ahmad et al., 1990	10°C	$1 601 000/year
9JEG	Jegede and Polley, 1992	19°C	£5 739 200/year

The network cost obtained in this work and the network cost reported in the literature are compared to the corresponding cost target reported in the literature in Figure 7.26.

As can be seen in Figure 7.26 most of the points lie around the cost ratio of one. The exception was Problem 16, 7FRAS1. For this case the network cost was found to be about five times as large as the cost target reported in the literature.

Nine out of ten (90%) of the network costs generated by the new technique achieved the targets reported in the literature. Six out of six (100%) of the solutions reported in the literature achieved the targets taken from the literature. Although the sample of the problems that are considered in this section is small it can be concluded that for this particular situation the cost targets reported in the literature were achievable.

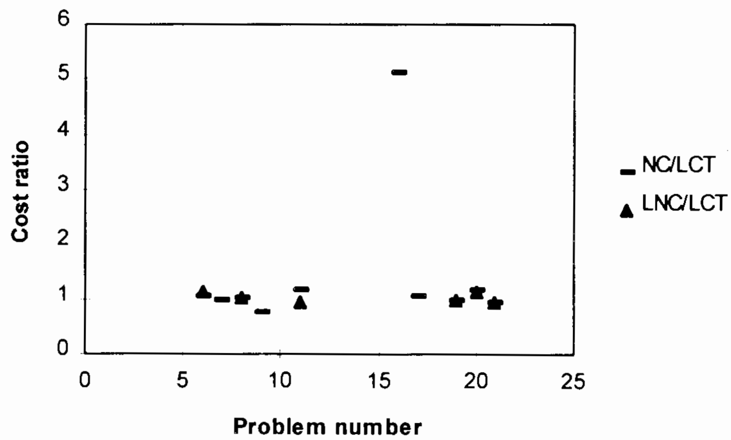

Figure 7.26: Comparison of the network cost obtained in this work (NC) and the network cost reported in the literature (LNC) to the cost target reported in the literature (LCT).

7.3.2.2.3 Comparison of the Network Cost to the Cost Target Generated by the Pinch Design Method Using UCTNET.

The comparison of the network cost to the cost targets generated with the aid of UCTNET is shown in Figure 7.27. Although about 68% of the network designs generated by the new technique were close to the cost targets, the remaining percentage of networks was off target. A similar trend was observed in the case of the network costs reported in the literature.

The network cost could be as much as 8 times the value of the cost target generated with the aid of UCTNET. This observation can be explained by saying that either the targets generated with the aid of UCTNET were sometimes too small to be achievable or the network design was very poor. The fact that the same trends were observed for both the networks generated in this study and those obtained from the literature would suggest that sometimes the targets generated with the aid of UCTNET might be too small to be achievable. This assertion may be examined by comparing the trends observed in this particular situation to similar conditions involving the average cost targets and the other cost targets obtained from the literature

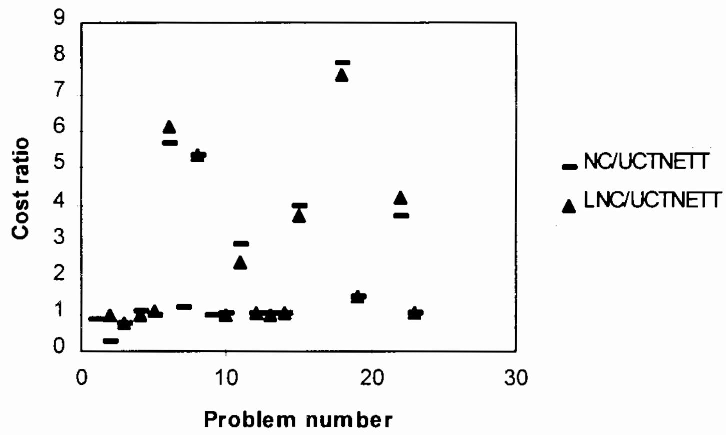

Figure 7.27: Comparison of the network cost obtained in this work (NC) and the network cost reported in the literature (LNC) to the cost target obtained with the aid of UCTNET (UCTNETT).

In the following section the cost targets determined with the aid of UCTNET and the cost targets obtained from the literature are compared to the average cost target.

7.3.2.2.4 Comparison of the Cost Target Generated by the Pinch Design Method Using UCTNET and the Cost Target Reported in the Literature to the Average Cost Target.

The cost targets used to evaluate the network costs determined in this study and the network costs obtained from the literature are listed in Table 7.20. The average cost target (ACT), the cost target obtained with the aid of the computer program UCTNET (UCTNETT), and the cost target reported in the literature (LCT) are compared with one another.

There is no obvious relation between the targets obtained by the different methods. The percentage differences are in the range of 2.7% (6SP1) to 599% (7FRAS1).

Table 7.20: Relation between the cost targets used to evaluate the network cost in this study.

Problem	Cost Limit ($/year)		Cost Target ($/year)		
	LCB	UCB	ACT	UCTNETT	LCT
3SP1	65	26 533	877	1 166	-
3NIS	0	166 028	1328	1 517	-
4SP1	7 496	105 227	13 164	13 744	-
4SP2	12 552	400 219	26 143	18 993	-
4TC2	2 194	86 823	5713	14 878	-
4YEE1**	54 000	795 773	561 433	132 410	714 000
4YEE2	36 200	133 476	53 590	64 807	79 850
4YEE3	8 000	521 609	88 095	14 902	77 017
4FRAS	8 913	72 004	19 716	35 778	45 296
5SP1	33 368	260 264	40 333	37 773	-
5ZHU	2 295	72 736	67 443	19 253	48 975
6SP1	27 760	294 190	33 865	32 947	-
6YEE**	484 400	1 007 539	544 481	577 117	-
7SP1	22 152	307 004	32 161	28 511	-
7CIR	5 675	376 841	74 944	28 986	-
7FRAS1#	243 311	25 821 093	13 538 587	-	1 937 000
7FRAS2#	2 185 836	5 039 515	2 328 181	-	3 257 000
7YEE	10 014	267 936	154 897	19 976	-
9ZHU	46 320	6 393 408	1 182 014	1 922 851	2 890 000
9AHM	767 250	2 920 942	2 008 528	-	1 601 000
9JEG*	84 200	10 898 354	2576 772	-	5 739 200
10BYF	68 000	1 436 335	330 811	91 764	-
10SP1	34 048	385 669	45 944	41 540	-

The question to be answered is which of the targeting techniques used consistently produces cost targets that are close enough to the global optimum. Since there is only one global optimum for each network problem cost targets should not differ by a big margin (say more than 10%) from each other and from the network optimum. Until this condition is satisfied it would seem cost targets are not likely to be consistent reference points for the evaluation of network designs. It must be stressed though that targeting is a useful aspect of network design.

7.3.3 The Significance of Evolutionary Development

The design process adopted in this study consists of two major stages. The first stage is the generation of a preliminary network (match sequencing). The second stage is improvement of the preliminary network through cost reduction (evolutionary development). In this section the impact of evolutionary development on network optimality is assessed. This is done by observing the annual cost of the network before and after evolutionary development.

Cost reduction by evolutionary development can be slight or significant, as shown in Table 7.21. This table shows that cost reduction by evolutionary development of the case study problems varied from 1 to 74%. The average cost reduction was about 14%. Except for the cost reduction of 74%, the annual cost of most of the networks was reduced by less than 35 %.

These results show that, in general, major cost savings in network design by the new technique are achieved during match sequencing. The match sequencing stage results in a preliminary network structure that may need improvement. The extent to which a preliminary structure can be evolved into a near optimal network basically depends on the match sequence. In turn, the match sequence defines the network topology. It may be necessary to jump from one topology to another in order to achieve optimality. The major difficulty is to know which topology will lead to global optimality. The globally optimal network structure is not known.

The process of evolutionary development developed in this study is guided by the network annual cost. The network structure is manipulated continuously so long as loop or path optimisation leads to an overall network cost reduction. Paths and loops may be broken or created on the basis of cost reduction. During evolutionary development it becomes obvious that the annual cost of a network is constrained mainly by the inlet and outlet temperatures of the exchangers.

Table 7.21:Network annual cost before and after evolutionary development.

Problem	Network cost, $/year		% Cost Reduction
	Before Evolution	After Evolution	
3SP1	1 074	1 050	2
3NIS	1 475	384	74
4SP1	12 390	10 599	14
4SP2	24 793	21 144	14
4TC2	14 672	14 516	1
4YEE1	860 475	751 187	13
4YEE2	84 160	77 803	8
4YEE3*	122 625	79 872	35
4FRAS	36 026	35 540	1
5SP1	43 328	38 964	10
5ZHU	66 217	56 443	15
6SP1	35 866	35 005	2
6YEE	635 628	605 263	5
7SP1	31 487	30 423	3
7CIR	120 816	115 663	4
7FRAS1	14 079 436	9 935 458	29
7FRAS2*	3 874 461	3 440 293	11
7YEE	188 753	157 523	17
9ZHU	3 338 604	2 817 679	16
9AHM	2 039 972	1 886 900	8
9JEG*	6 680 109	5 417 257	19
10BYF	410 594	340 680	17
10SP1	44 303	43 739	1

Some of the decisions that are considered during network design concern stream splitting, minimum utility requirements, and the minimum number of units. These factors influence network optimality and are briefly discussed below.

7.3.4 Effects of Stream Splitting, the Minimum Utility Requirement, and the Minimum Number of Units on Network Optimality.

The concepts of stream splitting, minimum utility requirement, and minimum number of units have been associated with cost reduction. In this section counter-examples are given to illustrate the need for a deeper insight into the nature of networks.

7.3.4.1 Stream Splitting

In network design it is assumed that splitting some of the streams in the network can reduce the network annual cost. In this section it is illustrated that this may not always be true.

The second problem solved in this project was also solved by Nishida et al., 1977. Applying an algorithmic-evolutionary approach to network design, they began with a split and cyclic network, shown in Figure 7.28a.

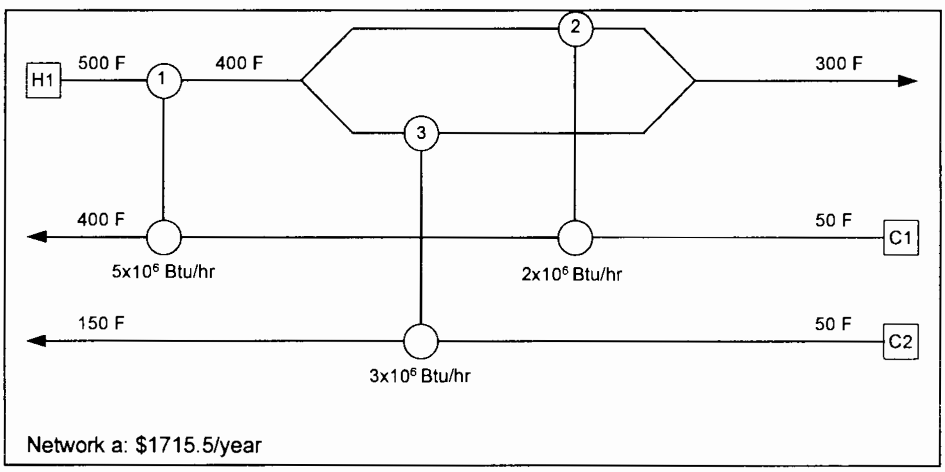

Figure 7.28a: The initial split and cyclic network solution to Problem 3NIS presented by Nishida et al., 1977.

The cost of the network shown in Figure 7.28a was $1 715.5/year. Further development of the network led to a split network that was not cyclic, shown in Figure 7.28b.

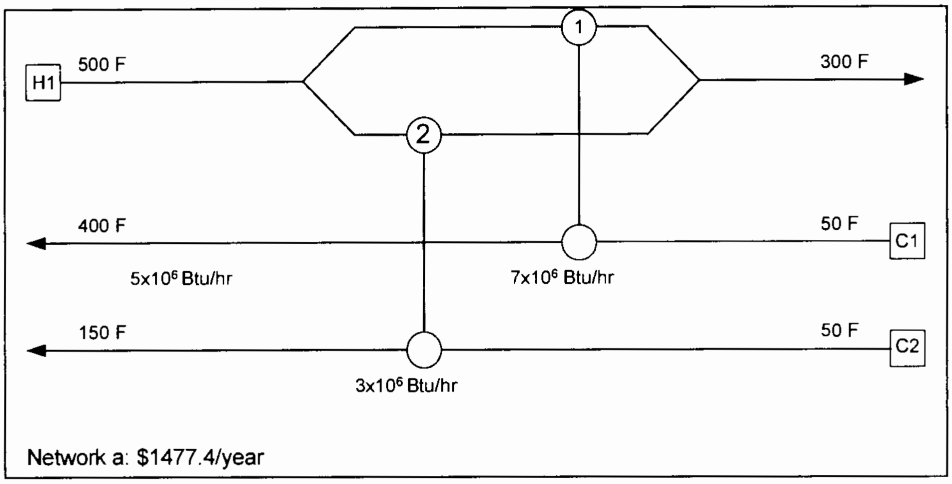

Figure 7.28b: Split network solution to Problem 3NIS derived from Figure 7.28a by Nishida et al., 1977.

The cost of the network shown in Figure 7.28b is $1 477.4/year. This network was improved to a final structure shown in Figure 7.28c.

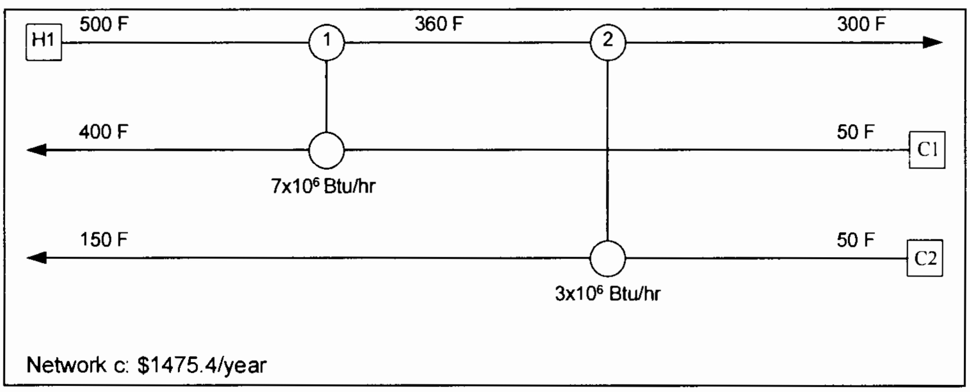

Figure 7.28c: Final network solution presented by Nishida et al. (1977) for the problem 3NIS.

The annual cost of the network shown in Figure 7.28c is $1 475.4/year. This example suggests that split and cyclic networks are not always minimum-cost networks. It is therefore necessary to know when and how streams should be split in order to achieve network optimality.

It is also necessary to know which streams should be matched more than once in order to generate optimal cyclic networks. Loop optimisation can be performed to test this condition.

7.3.4.2 **Minimum Utility Requirement and Minimum Number of Units.**

Intuitively, it would seem that a network that meets the minimum utility requirements and that has the minimum number of units is near optimal. One of the case study problems solved in this project shows that this is not always true.

The preliminary solution to Problem 6, 4YEE1, is shown in Figure 7.29a below.

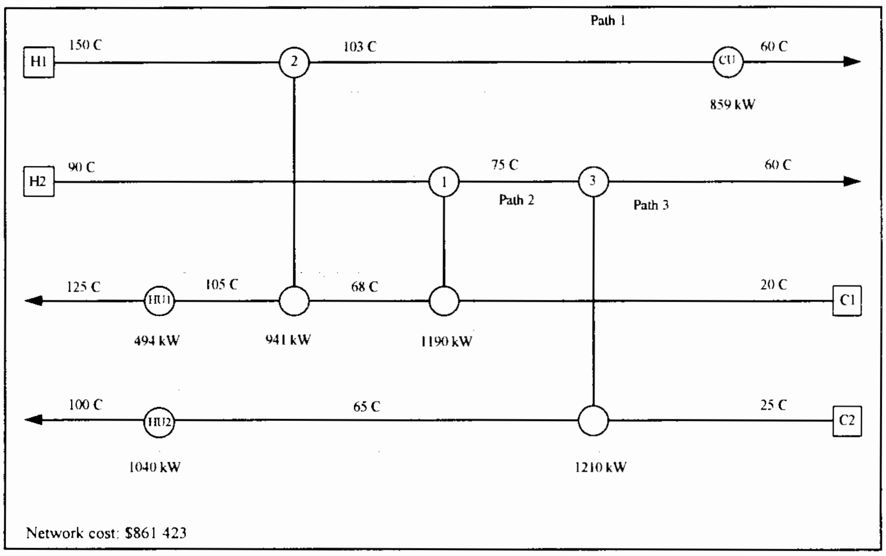

Figure 7.29a: Initial solution to Problem 6 (4YEE1).

The network shown in Figure 7.29a has 6 units. The total amount of hot utilities consumed is 1534 kW and the amount of cold utilities consumed is 859 kW. The total cost of this network is $861 423. Three paths, and no loops, were identified in the network. This suggests that it may be possible to evolve the network and reduce the network cost.

For this problem the minimum utility requirement was found to be 675 kW, while the minimum number of units is 4. After path manipulation, these conditions were reached. A design that meets these conditions is shown in Figure 7.29b. The total cost of this network is $1 333 335, and is 55% higher than the total cost of the initial network. Since the network shown in Figure 7.29b has no loops or paths, energy cannot be re-distributed among the units. If a choice were to be made between the design which meets minimum conditions but which is expensive, and the design which violates minimum conditions but is cheap, the preliminary network would be chosen.

It may be argued that Figure 7.29b is probably not necessarily the best minimum-number, minimum-utility network. The first question to this argument is whether or not the globally optimal solution has the minimum number of units and meets the minimum energy requirement. The second question is how the globally optimal network is found. The third question is that even if the globally optimal network has the minimum number of units and meets the minimum energy requirements and is, indeed, found there is no proof that the conditions of minimum number of units and minimum energy consumption apply to all globally optimal networks.

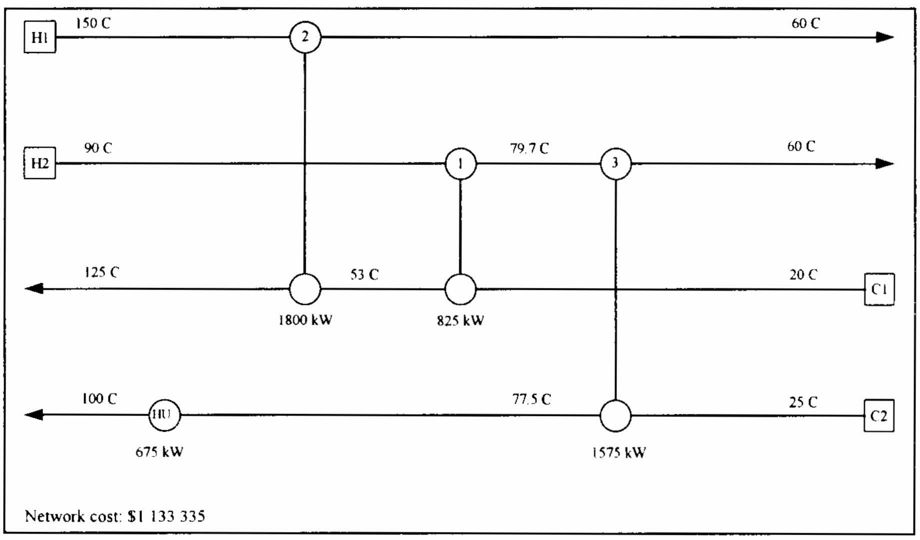

Figure 7.29b: Alternative solution to Problem 6 (4YEE1) which features the minimum number of units and meets the minimum utility requirements.

7.3.5 **The Significance of the New Approach**

The main feature of the stream matching technique developed in this study is that it is an experimental approach that is based on the basic heat exchange equation and the general cost correlation. A great deal of insight can therefore be gained by simulating the heat exchange process. In this study attention was focussed on the match as a building block for any network. Once the individual match is understood the next step is to investigate how a match interacts with another match.

The interaction of matches with one another is the basis of network design. The basic question of which match should be placed first in the network and how this match placement will affect the remaining matches has never been answered with certainty. It is for this reason that a fundamental understanding of the network structure should be developed. This approach is seen as a good starting point if difficult network design issues are to be resolved. Experimentation and evaluation of facts can form the basis for further development of network design as a whole.

A few facts were established or confirmed in this study. These facts are:

1. Network optimality is influenced by stream properties, economies of scale, process conditions, and the order in which the matches are arranged in the network;

2. Use of the minimum amount of utilities does not always imply global network optimality;

3. The relation between network optimality and the number of units is not obvious. Although the minimum number of units has been believed to be a necessary condition for network optimality, a network that has a larger number of units may be cheaper than a network that has the minimum number of units;

4. Stream splitting may or may not result in a network cost reduction. It is still not clear when streams should or should not be split. Even more disturbing is the fact that the cost implication of stream splitting has generally been ignored;

5. A large proportion of the cost savings is achieved at the preliminary stage of the design process. A lesser but significant proportion of the cost savings can achieved during evolutionary development;

6. There is no definite evaluation criterion for network performance. Network optimality has never been proven.

7. Although much work has been done to develop targeting methods, there are no criteria that can be used to evaluate the cost targets. As a result, different techniques may produce different cost targets for the same network problem. This situation needs to be weighed against the fact that there is only one globally optimal annual cost for each network problem.

8. The specification of minimum requirements such as the minimum approach temperature may result in additional constraints that may result in the exclusion of the global optimum from the solution set.

The insight gained sheds more light on the complexity of heat exchanger networks. It should be obvious that unresolved issues will limit further progress in the field of heat exchanger synthesis.

7.3.6 Weaknesses of the Technique

A number of disadvantages that are associated with the new technique are listed below.

1. The technique relies completely on a computer. It cannot be implemented by hand. Its further development will require computer-programming skills. Eventually there will be a need for a commercially available computer program for solving network design problems.

2. The stream arrangement procedure has not been automated. Only the match-sequencing algorithm has been automated. The program is not yet suitable for public or commercial use.

3. Evolutionary development as followed in this study is tedious if done by hand using a spreadsheet. There is therefore a need for automation of the evolutionary development procedure.

4. The technique does not provide answers to some basic network design questions such as proof of optimality, whether or not streams should be split, or the order in which paths and loops should be optimised during evolutionary development.

5. The technique has only been tested on a small sample of network design problems of three to ten process streams. The consistency of the technique has therefore not been proven.

Summary

The purpose of this chapter was to evaluate the new stream matching technique. Solving twenty-three network design problems ranging in size from three to ten process streams performed the evaluation. The solutions to these problems were compared with the corresponding solutions reported in the literature. Different workers using different network design techniques found the solutions reported in the literature.

The network solutions generated in this study were generally comparable to the solutions reported in the literature. The worst solution found in this study was about 10.5% higher than the solution reported in the literature. Ninety-four percent of the solutions were within 10% of the corresponding solutions reported in the literature. Seventy-two percent of the solutions were at most 3% higher than the corresponding solutions taken from the literature. Forty-four percent of the solutions were better than their literature counterparts. However, these comparisons are not strictly decisive because of uncertainties associated with the different assumptions and solution conditions. For instance, some designers may impose some restrictions on the solution, or use slightly different stream or cost data.

It was observed that the major proportion of cost savings is achieved during match sequencing. A smaller but significant proportion of the savings is achieved during evolutionary development. Optimising paths and loops in the network performed evolutionary development. Path and loop optimisation was performed by monitoring the network annual cost as a function of energy distribution along the path or around the loop. The network annual cost was found to be a monotonic function of energy distribution along the path or around the loop. Cost savings were based on the upper cost bound, a condition in which there is no energy recovery. The lower and upper cost bounds defined in this study are reproducible. They are not dependent on the network design technique.

A difficulty was experienced during evaluation of individual network solutions. It seemed there is no single maximum allowable values of the network performance index and the cost range ratio that can be used as evaluation criteria. The difficulty was to find values that are derived from the stream and cost data defining individual problems.

Although cost targets are useful in guiding network design, it was discovered that different techniques might produce different values for the same problem. For this reason cost targets are not consistent reference points for network evaluation. While some cost targets may fall outside the achievable range of network annual costs, others may be much larger than the corresponding global optima. There is a need for evaluation of cost targets.

In this chapter it was illustrated that stream splitting does not always enhance network optimality. It was further demonstrated that a design that meets both conditions of the minimum utility requirement and the minimum number of units might be more expensive than a design that does not meet these minimum requirements.

As far as network optimality is concerned, it was shown that specification of the minimum approach temperature could sometimes be associated with a cost penalty.

The strength of the new technique is that the match, as a building block for a network, can be optimised and characterised. This condition makes it possible to automate match sequencing, which accounts for the major cost savings. Once the preliminary network has been found by the match sequencing stage interactions among matches in the network with respect to the network annual cost can be studied. Matches can be eliminated or created and the effect of this step can be observed by monitoring the network annual cost. Hence the effects of various factors that influence network optimality can be studied at a match level or at a network level.

Further development of the new technique will need computer skills because it involves many repetitive calculation steps.

With reference to the best results reported in the literature, the technique consistently generated good results.

CHAPTER 8
Conclusions and Recommendations

8.1 Conclusions

The synthesis of heat exchanger networks is a complex problem. The problem is non-linear and combinatorial. Different network design techniques have been developed and used by different workers over the years to solve the problem. Significant cost savings have been achieved both theoretically and practically. Despite the impressive progress made in heat exchanger network synthesis some key issues remain unresolved. Examples of such issues are which streams should be matched first, which streams should be split and in what proportions, proof of network optimality, network controllability, operability and resilience.

Despite the progress made in heat exchanger synthesis over the years, there is a need to increase the understanding of the problem. Although many different network design techniques have been used to solve the problem it is important to know if a single technique can consistently handle a wide variety of design situations. The different design situations are problem size, minimum energy recovery specification (such as ΔT_{min}), different materials of construction, temperature restrictions, match restrictions, and different stream properties.

In this study the purpose was to develop a new network design technique that can consistently generate near optimal network solutions. Consistent generation of near optimal solutions can contribute toward a more fundamental understanding of heat exchanger networks and the design of more cost-efficient heat recovery schemes.

Using the basic heat exchange equation and the general cost correlation, a two-stage optimisation technique was developed. At the match level the annual cost of a match is a unimodal function of the minimum approach temperature. At the network level the annual cost of the network is a unimodal function of energy distribution along a path or around a loop. The overall technique consists of two major steps. The first step is match sequencing and it accounts for the major cost saving. The second step is evolutionary development and it accounts for a lesser but significant cost saving. These cost savings vary from one problem to another.

The technique was evaluated by solving twenty-three network problems taken from the literature. Different workers using different techniques previously solved the problems.

The basis for network evaluation was the cost. The network costs obtained by the new technique were compared to the lowest corresponding network costs reported in the literature. The worst result obtained by the new method was 10.5% higher than the result reported in the literature. Out of 18 problems whose results were reported in the literature 94% of the results obtained in this study were within 10% of the best results reported, and 44% were better than the results reported. On the basis of these results the conclusion is that the new technique is reasonably consistent in its generation of good network solutions. For some of the problems no solutions could be found in the literature. Therefore it was necessary to consider an alternative way of evaluating the results. The possibility of using cost targets as criteria for evaluating network designs was explored.

A tremendous amount of work has been done on targeting in the past. It was observed that there were no evaluation criteria for the design cost targets. For the same problem design targets obtained by different techniques could be different. This situation is not very meaningful given the fact that there is only one global optimum for any given problem. The consequence of the lack of evaluation criteria for cost targets is that some values may be too small to be achievable, while others may be too large to guide the design to a global optimum. These observations led to the conclusion that cost targets may not consistently provide conclusive evidence of the quality of a network design.

There are two problems that are associated with the evaluation of network performance. The primary problem is that the global optimum for each network problem is not known. The global optimum is the ideal point of reference for network evaluation. The secondary problem is that a consistent point of reference for network evaluation was not known. The network performance index (NPI) relates the network annual cost to the lower and upper cost bounds and it gives an indication of the cost savings. The cost range ratio (CRR) compares the network annual cost to the cost target. The problem was to define a near optimal network design in terms of the network performance index and the cost range ratio. Fixed values of the network performance index and the cost range ratio are not reliable criteria for network evaluation. Whatever criteria are chosen for network evaluation must be derived from the stream and cost data of individual problems.

Most of the solutions to the standard literature problems (4SP1, 4SP2, 5SP1, 6SP1, 7SP1, and 10SP1) were confirmed. Many workers using different techniques have solved these problems. Confirmation of these results may suggest that global optima have been found, even though this has not yet been proved.

In this study it was found that there is no obvious and direct correlation between the cost-optimum network design and the number of units in the network. A network design that has a fewer number of units may be more expensive than a network that involves a larger number of units. It was also observed that a network design that involves more than the minimum number of units might be cheaper than a design that involves the minimum number of units. These observations are significant since it is always desirable to know in which direction to steer the design in order to achieve optimality.

It is necessary to develop a network evaluation procedure that is based on some fundamental principles. This would be a more reliable approach to network evaluation because the results reported in the literature, even though useful, are not necessarily global optima. Furthermore, the number of solutions reported in the literature is limited to a few examples compared to the number of all the possible network design problems. Knowledge of the global optimum is necessary for an objective performance evaluation and for unveiling the solutions to unresolved issues. In short, there is a need for the development of a rigorous approach to network design.

The main advantage of the new technique is that it is experimental in approach. The procedure is based on the simulation of the heat exchange process using the basic heat exchange equation and the general cost correlation. Using this approach the effects of different factors that influence optimality can be established. This is a reliable way to test assumptions and to take guesswork out of network design. Potentially, this approach could lead to a rigorous theory for heat exchanger network design.

The major disadvantage of the new technique is that it is not fully developed at this stage. It has been tested only on a small sample of network problems and therefore its consistency has not been proven. Further development will include computer programming.

8.2 Recommendations

The network design technique developed in this work can be improved dramatically. The scope for further development can be viewed in two major aspects, namely, theory and implementation.

8.2.1 Development of the Theoretical Aspect of the Technique

The concepts developed in this study need to be developed into generalisations that can lead to the establishment of a rigorous heat exchanger network design theory. This will involve the basic heat exchange equation; the general cost correlation, thermodynamic constraints, and mathematical formulation. Some of the areas in which there is a potential for further development are listed and briefly discussed below.

1. *Match Selectivity*

   Match selection is the key step in network design. If the match selection criteria and the consequent match sequencing promote the overall network optimality then it should be possible to consistently generate network designs that are near optimal. The match selection criteria developed in this work can still be revised and then refined to ensure network optimality. Rigorous match selection and sequencing criteria can be used to determine and prove global optimality. Such design situations as phase changes and constraints imposed on a network should be accommodated in the match selection step in such a way that network optimality is achieved under those conditions.

2. *Stream Splitting and its Cost Implications*

   One of the network design issues that has not yet been resolved is when, how, and which streams should be split in order to achieve overall network optimality. In order to maintain the optimum split ratios some flow control has to be considered. An issue of secondary importance is whether or not stream splitting introduces a significant amount of the cost of control equipment.

3. *Network Evolution*

Although the major proportion of cost savings is achieved during the match sequencing stage, the network cost can sometimes be reduced by a significant amount through evolutionary development. In order to make the evolutionary process more efficient it is necessary to understand the interactions among paths and loops. Questions to be answered are whether or not paths and loops should be broken and in what order this should be done in order to achieve network optimality.

4. *Determination of the Global Optimum*

A network design may be close enough to the global optimum and therefore for practical purposes it may not be necessary to achieve the global optimum itself. But for purposes of performance evaluation it would be advisable to know how close the network cost is to the global optimum. Therefore there must be a way of finding at least the theoretical global optimum.

5. *Proof of Global Optimality*

Given the cost of a final network design it should be possible to examine the result and show whether or not it is the global optimum. This knowledge can be used to determine whether or not it is necessary to improve the result in question.

6. *Consistently Realistic Cost Targets*

In this study a lower cost bound and an upper cost bound were defined. Any cost target that falls outside the cost range starting from the lower cost bound and ending at the upper cost bound would seem unrealistic. But even if the cost target is in this cost range it may still not be realistic. This can happen, for instance, if the cost target is larger than the lower cost bound but lower than the global optimum. The reason for this possibility is that the lower cost bound should, in fact, be the global optimum. It is necessary, therefore, to find a way of testing whether or not a cost target is lower than the global optimum. A cost target that is lower than the global optimum can challenge the network designer to improve the network design.

7. *Criteria for the Evaluation of Network Performance*

   Evaluation of the performance of existing and new network designs is very important if progress is to be made in the field of heat exchanger network synthesis. The evaluation results should accurately and consistently tell the network designer how far the current network design is from the best possible network design. This is only possible if there are sound network performance criteria in place. If a network design can be evaluated the influence of different factors on network optimality can be determined.

8. *Interfacing Heat Exchanger Design and Heat Exchanger Network Design*

   Practically, it would seem that heat exchanger network design should be an extension of heat exchanger design. In other words there should be agreement between the principles governing individual heat exchanger design and those governing heat exchanger network design. Only then can the impact of heat exchanger network design on plant design be accurately assessed.

8.2.2 Development of the Implementation Aspect of the Technique

The implementation of the technique will undoubtedly involve a computer program. The computer program can be developed to perform calculations needed for the network designs, and to evaluate the network designs.

1. An algorithm should be developed that identifies paths and loops, and then performs evolutionary development.

2. A program that integrates detailed heat exchanger design and heat exchanger network design needs to be developed in order to study the impact of heat exchanger network design on realistic network design problems.

3. A procedure that simulates heat flows in a network needs to be developed in order to study such unresolved issues as network controllability and resiliency. Such a procedure can be used to study the characteristics of networks.

4. In order to maximise benefits that can be gained from the new network design technique it would be necessary to make the network design program user-friendly, interactive, and robust.

5. It would be useful to design the program in such a way that it can be run in an automatic mode or a manual mode. It should be possible to switch from one mode of operation to another at any point of the run specified by the user.

6. An ambitious step in the development of the new design technique would be to develop it into an online energy optimiser. At this level the program could be used to monitor utility consumption on a continuous basis.

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APPENDICES

Commonly Used Terms

Commonly used terms are defined in this section. These terms are not arranged in alphabetical order.

- **Heat capacity flowrate** - Product of the heat capacity and the mass flowrate. This quantity is denoted by the symbol F_{cp}.

- **Temperature-enthalpy diagram** - A plot of stream temperature versus stream enthalpy change (Figure A.1). The enthalpy value (in kW or Btu/hr) on the abscissa represents the product of the stream heat-capacity flowrate (kW/°C or Btu/(hr.°F)) and the hot-stream temperature drop or cold-stream temperature rise.

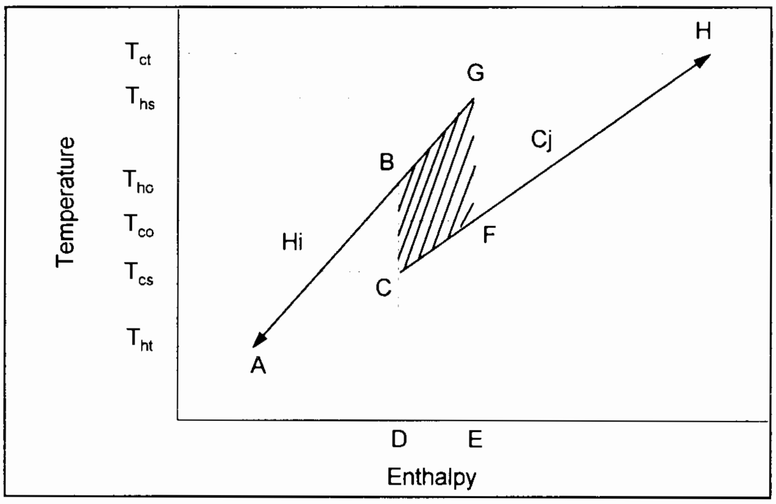


Figure A.1: Temperature-enthalpy diagram showing hot stream Hi and cold stream Cj.

In Figure A.1, T_{hs} and T_{cs} are the supply temperatures of the hot stream and the cold stream, respectively; T_{ht} and T_{ct} are the target temperatures of the hot and the cold streams, respectively.

- **Exchanger inlet temperature** - Temperature at which a stream enters an exchanger. In Figure A.1 the exchanger inlet temperature of hot stream Hi is T_{hs} and the exchanger inlet temperature of cold stream Cj is T_{cs}.

- **Exchanger outlet temperature** - Temperature at which a stream leaves an exchanger. In Figure A.1 the exchanger outlet temperature of hot stream Hi is T_{ho} and the exchanger outlet temperature of cold stream Cj is T_{co}.

- **Hot-end temperature difference** - In a counter-current exchanger this is the difference between the exchanger inlet temperature of the hot stream and the exchanger outlet temperature of the cold stream. In Figure A.1 this difference is (T_{hs} -T_{co}). The hot-end temperature difference is denoted by ΔT_{he}.

- **Cold-end temperature difference** - In a counter-current exchanger this is the difference between the exchanger outlet temperature of the hot stream and the exchanger inlet temperature of the cold stream. In Figure A.1 this difference is (T_{ho} - T_{cs}). The cold-end temperature difference is denoted by ΔT_{ce}.

- **Temperature-interval diagram (Grid diagram)** - A set of horizontal, directed line segments representing hot streams (pointing in one direction) and cold streams (pointing in the opposite direction). The starting point of each line segment represents the supply temperature, and the final point (arrow-head) represents the target temperature (Figure A.2). In this representation, a match, or the heat exchange, between two process streams, is designated by placing a pair of circles on each of the streams and connecting them with a straight vertical line. Utilities are represented by circles on the streams they heat or cool. Numerical values below the circles refer to the heat loads of exchangers, heaters, or coolers. Numbers inside the circles indicate the order in which the process matches were placed in the network.

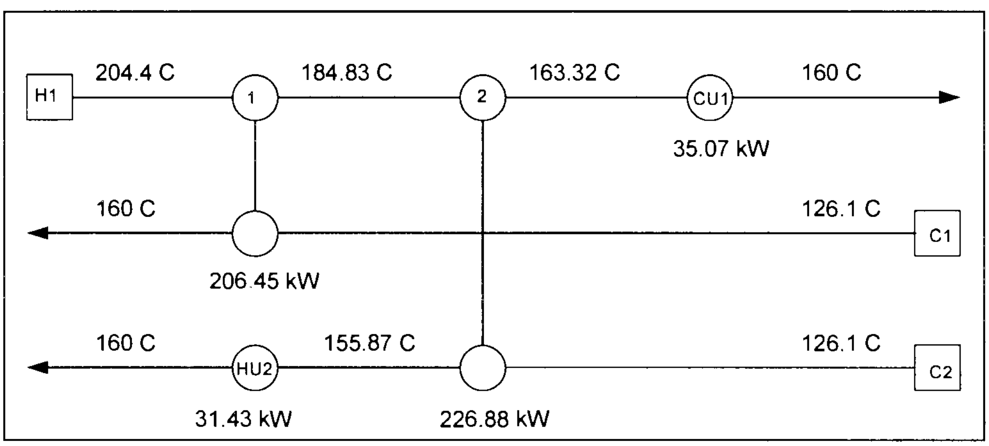


Figure A.2: Temperature-interval diagram (Grid diagram)

- **Acyclic network** - A network in which no stream exchanges heat more than once with another stream. The network shown in Figure A.2 is acyclic.

- **Cyclic network** - A network in which one stream exchanges heat more than once with another stream (Figure A.3). "In a cyclic network essentially the whole heat contents of hot streams can be transferred to that of cold streams, thus resulting in less use of utilities" (Liu,1987). In general, a cyclic network has a lower operating cost compared with an acyclic network (Liu,1987).

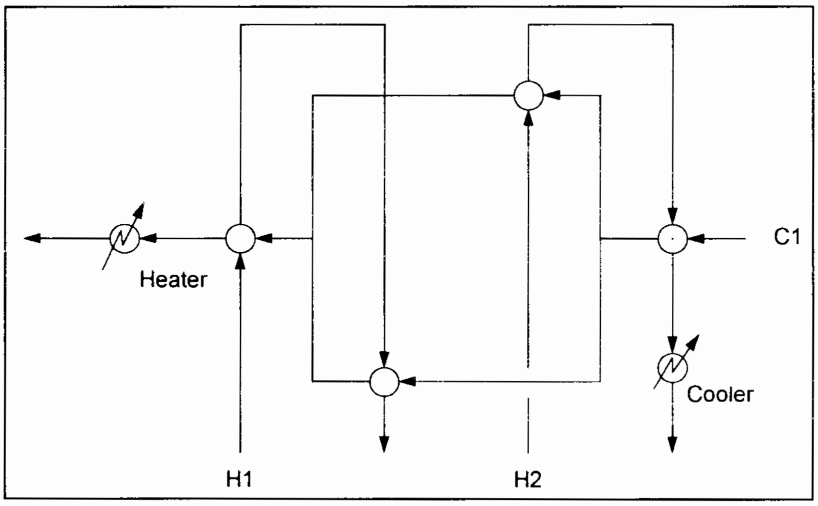


Figure A.3: An example of a cyclic network (Nishida et al., 1977)

- **Split network** - A network in which a stream is divided into two or more streams that are at the same temperature (Figure A.4). Here cold stream C1 is split into two streams which unite after heat exchange. Figure A.3 above also shows a split network. The use of stream splitting generally leads to networks of fewer units and lower investment costs (Liu,1987).

- **Minimum approach temperature (ΔT_{min})** - The smaller of the hot-end temperature difference and the cold-end temperature difference. In Figure A.1 the enthalpy changes linearly with temperature, and the minimum approach temperature is equal to the cold-end temperature difference:

$$\Delta T_{min} = (T_{ho} - T_{cs}).$$

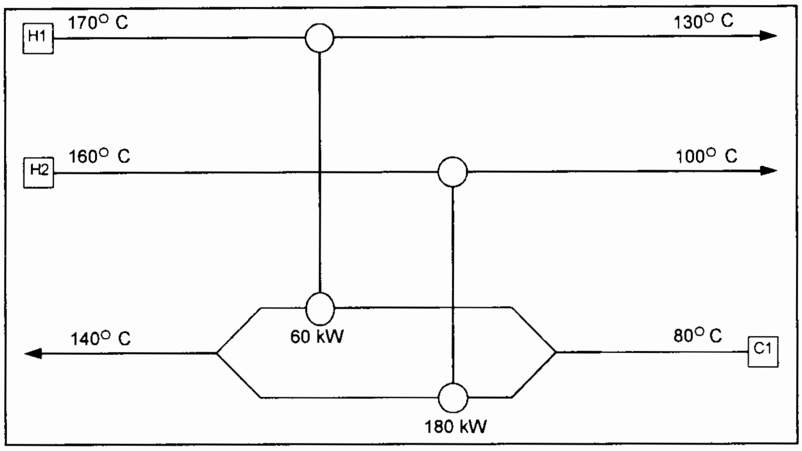


Figure A.4 - An example of a split network (Linnhoff and Ahmad, 1990)

- **Heat Recovery Approach Temperature (HRAT)** - The minimum approach temperature between the hot composite curve and the cold composite curve as plotted on a temperature-enthalpy diagram (Colbert, 1982). For a given value of the heat recovery approach temperature the minimum hot utility requirement ($Q_{h,min}$) and the minimum cold utility requirement ($Q_{c,min}$) for the problem can be determined. The quantities HRAT, $Q_{h,min}$, and $Q_{c,min}$ are shown in Figure A.5.

- **Exchanger Minimum Approach Temperature (EMAT)** - According to Colbert (1982), this "is the minimum temperature of approach within a single exchanger." It is the minimum approach temperature, ΔT_{min}, defined above. It can have a value that is less than or equal to that of the heat recovery approach temperature.

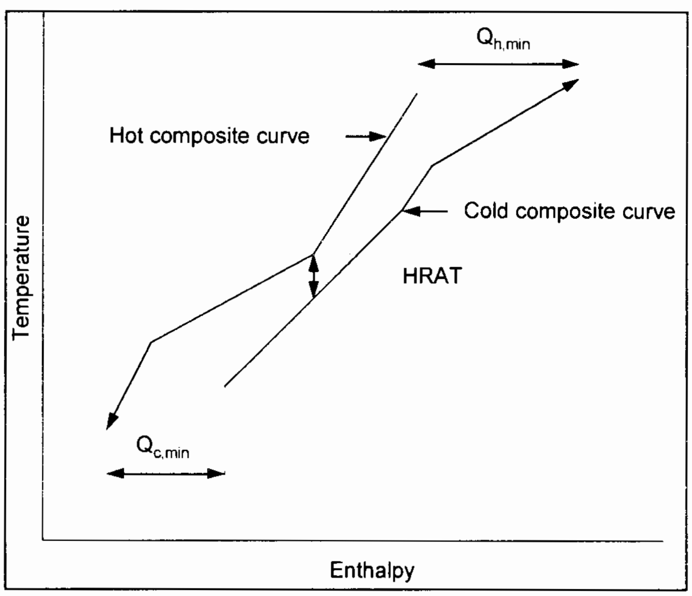


Figure A.5: Composite curves and the Heat Recovery Approach Temperature (HRAT).

- **Energy recovered** - Energy transferred from a hot process stream to a cold process stream. In Figure A.1 the energy recovered is the enthalpy difference (E - D).

- **Unit** - A process exchanger or a utility exchanger placed in a network.

- **Minimum number of units** - The smallest number of the sum of process and utility exchangers required to meet energy requirements in a network. The minimum number of units in network design is determined by using a simplified Euler relation. This equation is shown below :

$$u_{\min} = N + O - S \qquad (A.1)$$

where u_{min} = Minimum number of units

N = Sum of the process streams, hot utilities used, and cold utilities used,

O = Number of loops, and

S = Number of independent sub-networks.

Quantities whose values can be determined during the match optimisation process are listed below.

Quantities that are determined during match optimisation

1. *Energy recovered,* Q_r

The energy transferred from a hot process stream to a cold process stream. This quantity can be evaluated by the basic heat exchange equation (3.1).

2. *Exchanger inlet temperature of the hot stream,* T_{hi}

This is the temperature at which a hot process stream enters an exchanger.

3. *Exchanger outlet temperature of the hot stream,* T_{ho}

This is the temperature at which a hot stream leaves an exchanger.

$$T_{ho} = T_{hi} - \frac{Q_r}{F_h} \qquad (B.1)$$

4. *Exchanger inlet temperature of the cold stream,* T_{ci}

This is the temperature at which a cold stream enters an exchanger.

5. *Exchanger outlet temperature of the cold stream,* T_{co}

This is the temperature at which a cold stream leaves an exchanger.

$$T_{co} = T_{ci} + \frac{Q_r}{F_c} \qquad (B.2)$$

6. *Hot-end temperature difference,* ΔT_{he}

This is the positive difference between the exchanger inlet temperature of the hot stream and the exchanger outlet temperature of the cold stream.

$$\Delta T_{he} = T_{hi} - T_{co} \qquad (B.3)$$

7. *Cold-end temperature difference,* ΔT_{ce}

This is the positive difference between the exchanger outlet temperature of the hot stream and the exchanger inlet temperature of the cold stream.

$$\Delta T_{ce} = T_{ho} - T_{ci} \tag{B.4}$$

8. *Hot utility requirement in the low temperature range, $Q_{h\text{-}low}$*

This is the amount of hot utility required to heat a cold process stream from its supply temperature to its exchanger inlet temperature.

$$Q_{h-low} = F_c(T_{ci} - T_{cs}) \tag{B.5}$$

The temperature interval starting from the supply temperature and ending at the inlet temperature of the cold stream is the low temperature range, as shown in Figure B.6a.

9. *Hot utility requirement in the high temperature range, $Q_{h\text{-}high}$*

This is the amount of energy required to heat a cold process stream from its exchanger outlet temperature to its target temperature.

$$Q_{h-high} = F_c(T_{ct} - T_{co}) \tag{B.6}$$

The temperature interval starting from the outlet temperature to the target temperature of the cold stream is the high temperature range for this stream, as shown in Figure B.6a.

10. *Cold utility requirement in the low temperature range, $Q_{c\text{-}low}$*

This is the amount of energy required to cool a hot process stream from its exchanger outlet temperature to its target temperature.

$$Q_{c-low}=F_h(T_{ho}-T_{ht}) \tag{B.7}$$

For the hot stream, the low temperature range is the interval starting from the outlet temperature to the target temperature, as shown in Figure B.6b.

11. *Cold utility requirement in the high temperature range, $Q_{c\text{-}high}$*

This is the amount of energy required to cool a hot process stream from its supply temperature to its exchanger inlet temperature.

$$Q_{c-high} = F_h(T_{hs} - T_{hi}) \tag{B.8}$$

For the hot stream, the high temperature range is the interval from the supply to the inlet temperature, as shown in Figure B.6b.

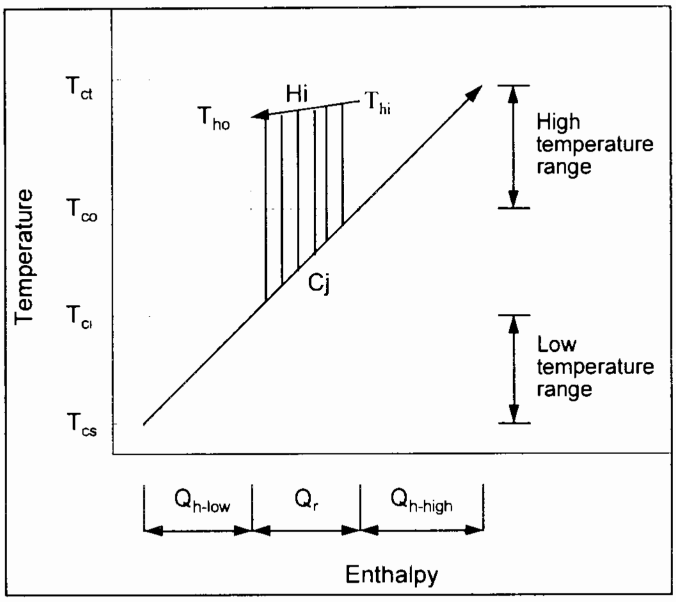


Figure B.6a: Hot utility requirements in the high and low temperature ranges.

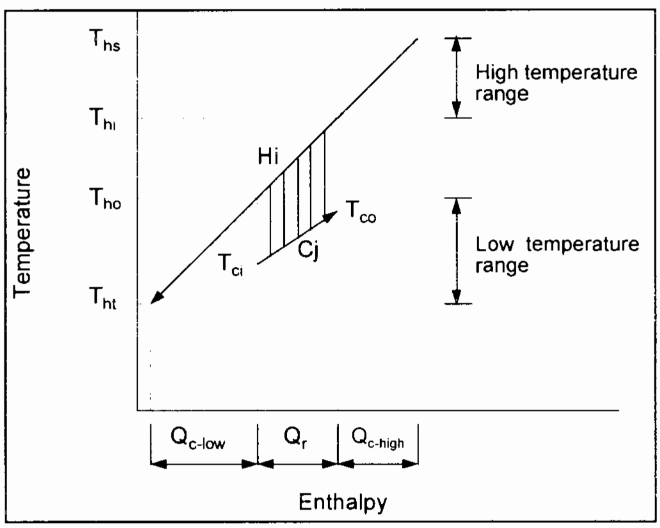


Figure B.6b: Cold utility requirements in the high and low temperature ranges.

12. *Process exchanger area, A_p*

Surface area over which energy is transferred from the hot process stream to the cold process stream in a process exchanger.

$$A_p = \frac{Q_r}{U.\Delta T_{LM}} \qquad (B.9)$$

The overall heat transfer coefficient U is given by:

$$\frac{1}{U} = \frac{1}{h_h} + \frac{1}{h_c} \qquad (B.10)$$

If $\Delta T_{he} \neq \Delta T_{ce}$ the logarithmic mean temperature difference, ΔT_{LM}, is given by:

$$\Delta T_{LM} = \frac{\Delta T_{he} - \Delta T_{ce}}{\ln(\frac{\Delta T_{he}}{\Delta T_{ce}})} \qquad (B.11)$$

If $\Delta T_{he} = \Delta T_{ce}$ then

$$\Delta T_{LM} = \Delta T_{he} = \Delta T_{ce} \qquad (B.12)$$

13. *Minimum approach temperature, ΔT_{min}*

The smaller of the hot-end temperature difference and the cold-end temperature difference.

If $\Delta T_{he} < \Delta T_{ce}$ then

$$\Delta T_{\min} = \Delta T_{he} \qquad (B.13)$$

If $\Delta T_{he} > \Delta T_{ce}$ then

$$\Delta T_{\min} = \Delta T_{ce} \qquad (B.14)$$

Else if $\Delta T_{he} = \Delta T_{ce}$ then

$$\Delta T_{\min} = \Delta T_{he} = \Delta T_{ce} \qquad (B.15)$$

The minimum approach temperature at which the total match cost is lowest is the optimum minimum approach temperature, ΔT_{opt}.

14. *Process exchanger flux, Q_r"*

Energy transferred from the hot stream to the cold stream per unit heat transfer surface area.

$$Q''_r = \frac{Q_r}{A_p} \tag{B.16}$$

or

$$Q''_r = U.\Delta T_{LM} \tag{B.17}$$

15. *Percent energy recovery, P_r*

This quantity is defined as the ratio of energy recovered to either the heat load of the hot process stream or the heat load of the cold process stream, whichever is smaller, multiplied by a hundred.

If $\Delta H_h < \Delta H_c$ then

$$P_r = \frac{Q_r}{\Delta H_h} \times 100\% \tag{B.18}$$

otherwise

$$P_r = \frac{Q_r}{\Delta H_c} \times 100\% \tag{B.19}$$

16. *Hot utility requirement, Q_{hu}*

This is the sum of the hot utility requirement in the high temperature range and the hot utility requirement in the low temperature range.

$$Q_{hu} = Q_{h-high} + Q_{h-low} \tag{B.20}$$

17. *Hot utility exchanger area, A_{hu}*

This is the surface area over which heat is transferred from the hot utility stream to the cold process stream. It is given by a relation similar to Equation (B.10). The calculation is done for both the low-temperature and high-temperature regions.

28. *Cold utility requirement, Q_{cu}*

This is the sum of the cold utility requirement in the high temperature range and the cold utility requirement in the low temperature range.

$$Q_{cu} = Q_{c-high} + Q_{c-low} \tag{B.21}$$

19. *Cold utility exchanger area,* A_{cu}

The surface area over which heat is transferred from the hot process stream to the cold utility stream. This quantity is given by a relation similar to Equation (B.10). It is determined for both the low-temperature and high-temperature regions.

20. *Total annual hot utility cost,* $C_{ce,hu}$

Sum of the annual capital cost of the hot utility and the annual cost of the hot utility.

21. *Total annual cold utility cost,* $C_{ce,cu}$

Sum of the annual capital cost of the cold utility and the annual cost of the cold utility.

22. *Process exchanger cost,* C_{Ap}

Annual capital cost of the process exchanger.

23. *Total annual cost,* C_{tot}

The total annual cost is the sum of the total annual hot utility cost, the total annual cold utility cost, and the annual process exchanger cost.

These quantities are stored in a Borland Pascal record structure. A typical record structure is shown as Table B.1 in Appendix B.

Table B.1: Record that contains match data.

MatchPointer = MatchRecord;

MatchRecord = Record

HotStream	: Real;
ColdStream	: Real;
T_{hi}	: Real;
T_{ho}	: Real;
T_{ci}	: Real;
T_{co}	: Real;
T_{hs}	: Real;
T_{ht}	: Real;
T_{cs}	: Real;
T_{ct}	: Real;
$Q_{h\text{-}low}$	: Real;
$Q_{h\text{-}high}$	: Real;
$Q_{c\text{-}low}$	: Real;
$Q_{c\text{-}high}$	: Real;
Q_r	: Real;
Process_Area	: Real;
DT_min	: Real;
DT_opt	: Real;
Flux	: Real;
P_r	: Real;
Q_h	: Real;
HU_Area	: Real;
Flux_hu	: Real;
Q_c	: Real;
CU_Area	: Real;
Flux_cu	: Real;
CapitalCost_HU	: Real;
TotalUtilityCost	: Real;
TotalHotUtilityCost	: Real;
CapitalCost_CU	: Real;
ColdUtilityCost	: Real;
TotalColdUtilityCost	: Real;
Total_cost	: Real;
Match_index	: Real;
ProcessCapitalCost	: Real;
coefficient_1	: Real;
coefficient_2	: Real;
index	: Real;
coefficient_1_HU	: Real;
coefficient_2_HU	: Real;
index_HU	: Real;
coefficient_1_CU	: Real;
coefficient_2_CU	: Real;
index_CU	: Real;
Rate_of_return	: Real;
Interest_rate	: Real;
Life_time	: Real;
Hours_in_operation	: Real;
h_h	: Real;
F_h	: Real;
h_c	: Real;
F_c	: Real;
$T_{hu\text{-}in}$	: Real;
$T_{hu\text{-}out}$	: Real;
h_{hu}	: Real;
$T_{cu\text{-}in}$	: Real;
$T_{cu\text{-}out}$	: Real;
h_{cu}	: Real;
HotUtilityUnitCost	: Real;
ColdUtilityUnitCost	: Real;
preferred	: Digital;
prohibited	: Digital;
infeasible	: Digital;
placed	: Digital;
c_{ij}	: Real;
Active_HU	: Integer;
Active_CU	: Integer;
MinimumFlux	: Real;
MinimumApproach	: Real;
MatchNumber	: Integer
Next	: MatchPointer

end.

i. Calculation of the Rate of Return on Investment

The rate of return on investment, δ, can be calculated quite easily if the rate of interest r and the useful service life span of a piece of equipment are known. The correlation used in this project was taken from Ahmad (1985) and Jegede and Polley (1992). It is used to express the capital cost of a piece of equipment on a yearly basis. This is done by multiplying the capital cost of the piece of equipment by the rate of return on investment. The result is the annualised cost of the piece of equipment.

If the interest rate is expressed as a percentage then the rate of return on investment is calculated by Equation C-i.1, and if the rate of interest is given as a fraction then the rate of return on investment is obtained from Equation C-i.2. Another term that has been used for the rate of return on investment is annualisation factor or annual capital recovery factor.

$$\delta = \frac{\left(1 + \frac{r}{100}\right)^{L}}{L} \qquad (C - i.1)$$

$$\delta = \frac{(1 + r)^{L}}{L} \qquad (C - i.2)$$

Example C-1.: Calculation of the rate of return on investment.

In an example discussed by Jegede and Polley (1992) the plant life is given as 5 years and the rate of interest is 10%. Therefore, for this situation Equation C-i.1 can be used to determine the rate of return on investment.

$\delta = [(1+ 10/100)^5]/5$

$= \underline{0.322}$

ii. Calculation of the Utility Unit Cost

Sometimes the cost of utilities is given as a unit of currency per unit mass of the utility consumed. In this project the mass of the utility consumed has been converted to the amount of energy consumed. This conversion then allows the cost of utilities to be expressed as a unit of currency per unit of energy per unit of time.

The conversion involves consideration of downtime, the specific heat capacity of the utility, and the change in temperature, if sensible heat is involved. That is, if the utility is not undergoing a phase change.

If the utility is undergoing a phase change, then the heat of transformation is used instead of the product of the specific heat capacity and the temperature change. These situations are illustrated below.

Suppose the cost of utilities is given as Rand per kilogram, R/kg. Then it may be desirable to convert this unit into Rand per kilowatt per year, R/(kW.yr).

Let:

c	= specific heat capacity of the utility;
ΔT	= change in temperature;
t	= down time in hours per year;
t_{op}	= time in operation in seconds per year;
ΔH_s	= heat of transformation of the fluid

Given the down time t, the time in operation is calculated by Equation C-ii.1:

$$t_{op} = \{[(\frac{365\ days}{year}) \times (\frac{24 hours}{day})] - t\} \times (\frac{60\ minutes}{hour})(\frac{60\ seconds}{minute}) \qquad (C - ii.1)$$

If the utility is not undergoing a phase change the conversion from R/kg to R/(kW.yr) is carried out by using Equation C-ii.2. If the utility is exchanging heat at a constant temperature (phase change), Equation C-ii.3 is used.

$$\$/(kW.yr) = \$/kg \times \left(\frac{t_{op}}{c\Delta T}\right) \qquad (C-ii.2)$$

$$\$/(kW.yr) = \$/kg \times \left(\frac{t_{op}}{\Delta H_s}\right) \qquad (C-ii.3)$$

In Equations C-ii.2 and C-ii.2 the units of energy and power are kJ and kW, respectively. Other units of energy and power can be used, if consistent.

Example C-2: Calculation of the unit cost of utilities.

The data for steam and cooling water are given in Table C-1. The conversion of the cost of utilities from \$/kg to \$/(kW.yr) is illustrated below.

Table C.1: Data (Liu, 1987) used to illustrate the conversion of the cost of utilities from \$/kg to \$/(kW.yr).

Steam	
Latent heat, kJ/kg	1527.17
Temperature, °C	282.22
Equipment down time, hr/yr	380
Cost of steam, \$/kg	2.2046×10^{-3}
Cooling water	
Heat capacity, kJ/kg-K	4.1840
Temperature, °C	37.8
Maximum water output temperature, °C	82.2
Equipment down time	380
Cooling water cost, \$/kg	1.1023×10^{-4}

The down time is the same for all exchangers. Therefore the period over which the equipment is on line is the same:

t_{op} = [(365 x 24) - 380] x 60 x 60 sec/yr = <u>30.168 x 10^6 sec/yr</u>

<u>Unit cost of steam, C_{hu}</u>

C_{hu} = \$2.2046 x 10^{-3}/kg x (30.168 x 10^6 sec/yr)/(1527.17 kJ/kg)

= <u>\$43.55/(kW.yr)</u>

<u>Unit cost of cooling water, C_{cu}</u>

C_{cu} = \$1.1023 x 10^{-4}) x (30.168 x 10^6 sec/yr)/[{4.1840 kJ/(kg.K)}{82.2 K - 37.8 K}]

= <u>\$17.9/(kW.yr)</u>

Match configurations

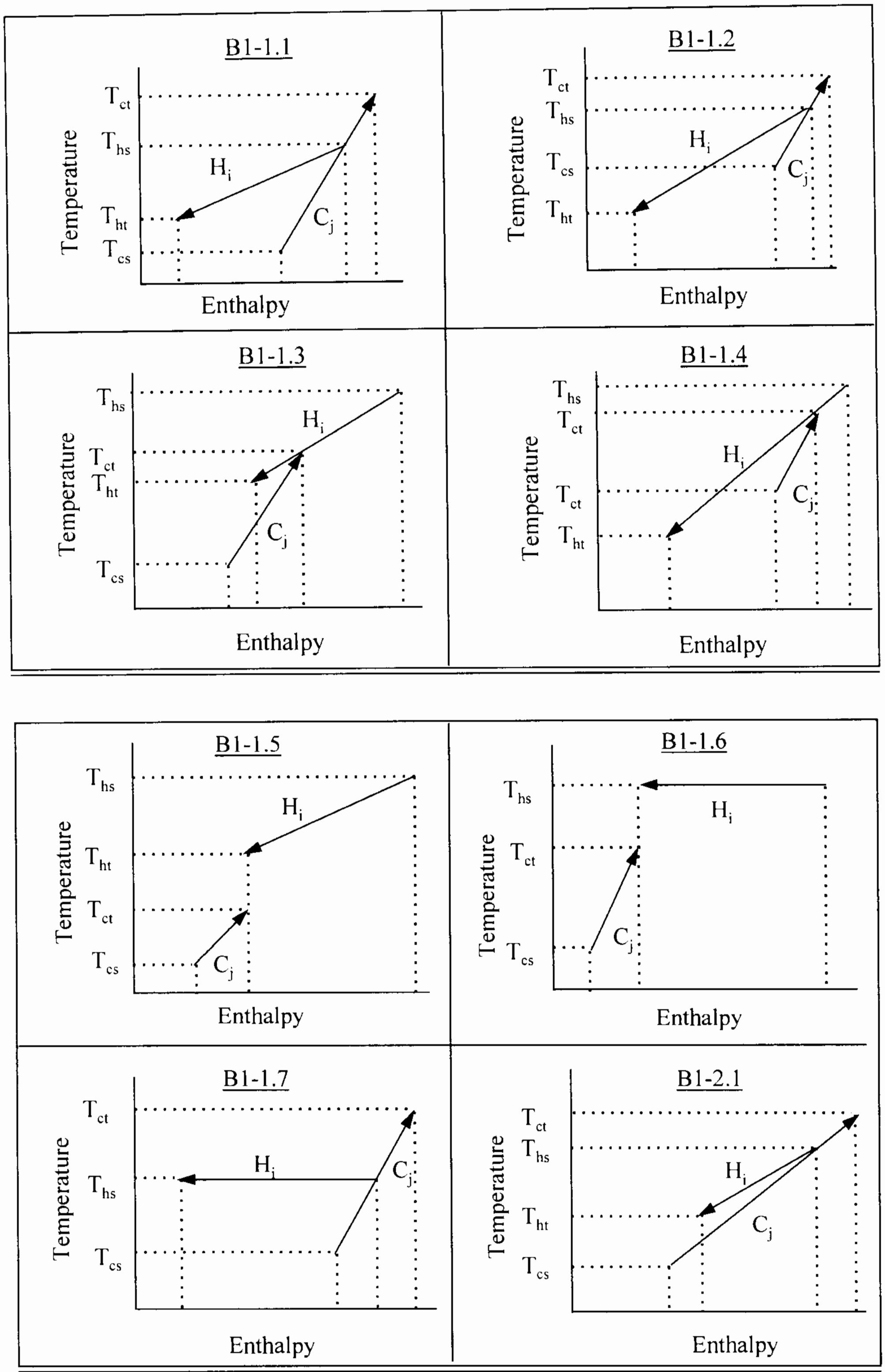
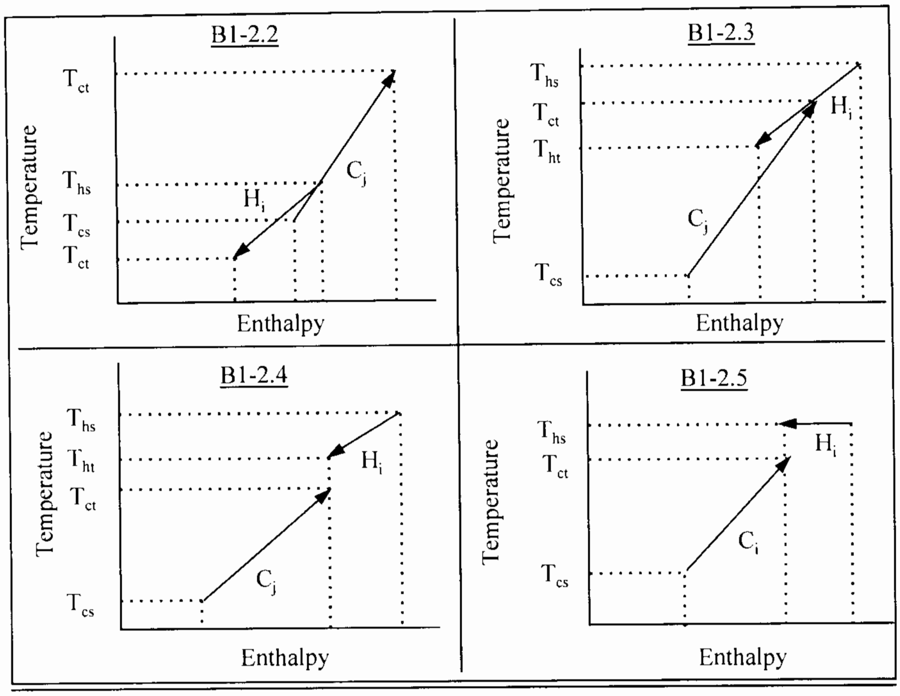


Figure D: Match configurations.



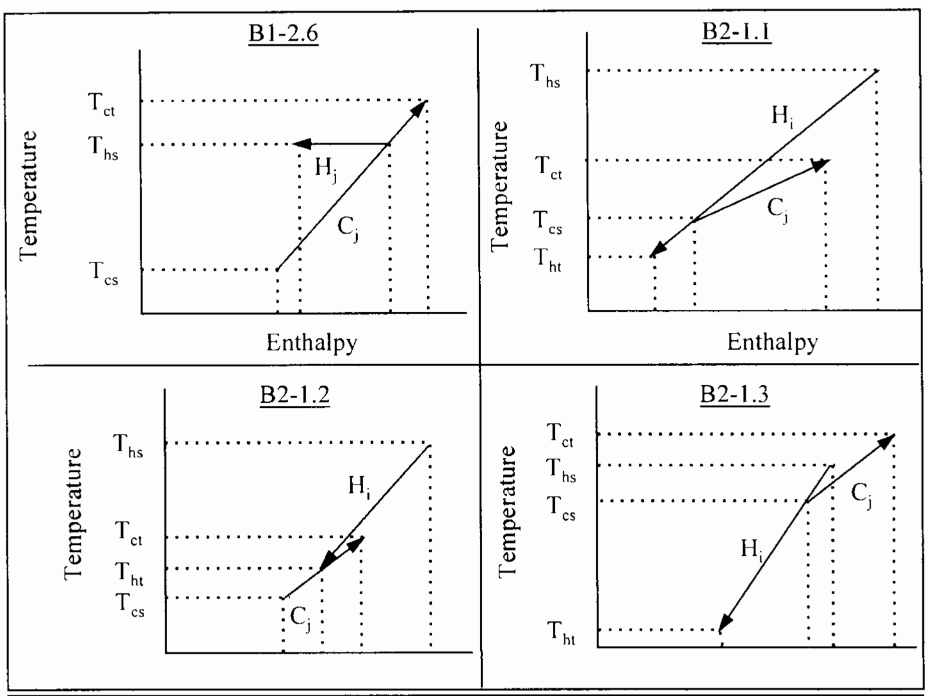


Figure D: Match configurations (continued).

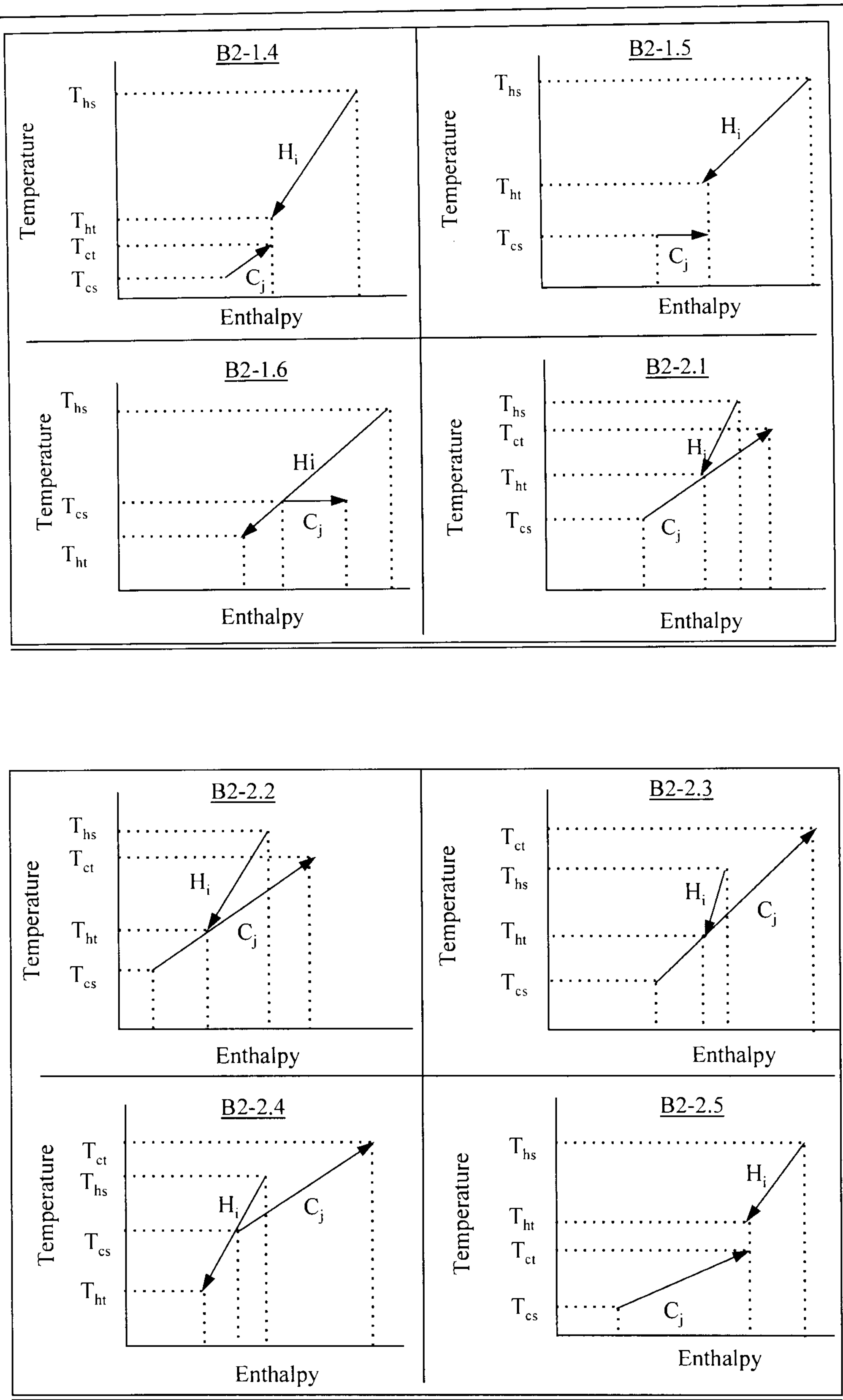


Figure D: Match configurations (continued).

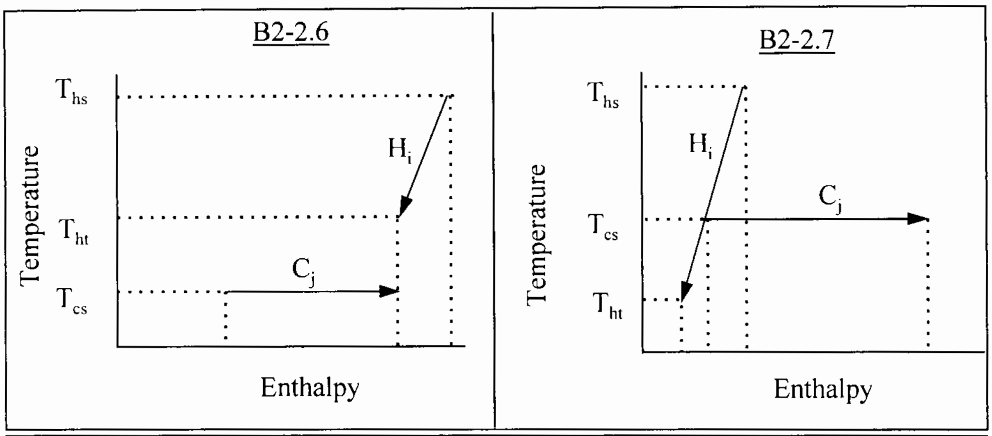


Figure D: Match configurations (continued).

CASE STUDY PROBLEMS

Problem 1: 3SP3

Stream	T_s (°C)	T_t (°C)	F_{cp} (kW/°C)	h ($kWm^{-2}K^{-1}$)
H1	204.4	160.0	10.55	1.70342
C1	126.1	160.0	6.09	1.70342
C2	126.1	160.0	7.62	1.70342
HU	282.22	282.22	-	3.40681
CU	37.80	82.20	-	1.70342

Cost data

Cost of heat transfer area A (m^2), $	$= 1\ 456.3A^{0.6}$
Annual rate of return δ	= 0.1
Cooling water cost, $/(kW.yr)	= 17.9
Steam cost, $/(kW.yr)	= 37.26

Problem 2: 3NIS

Stream	T_s (°F)	T_t (°F)	F_{cp} (Btu/(hr. °F)	h (Btu/(hr.ft^2.°F)
H1	500	300	50 000	300
C1	50	400	20 000	300
C2	50	150	30 000	300
HU	456	456	-	600
CU	100	180	-	300

Cost data

Cost of heat transfer area A (ft^2), $	$= 350A^{0.6}$
Annual rate of return δ	= 0.1
Cooling water cost, $/((Btu/hr).yr)	= 0.0053125
Steam cost, $/((Btu/hr).yr)	= 0.0110749

Problem 3: 4SP1

Stream	T_s (°C)	T_t (°C)	F_{cp} (kW/°C)	h ($kWm^{-2}(°C)^{-1}$)
H1	160.00	93.30	8.79	1.70342
H2	248.90	137.80	10.55	1.70342
C1	60.00	160.00	7.62	1.70342
C2	115.60	260.00	6.08	1.70342
HU	282.22	282.22	-	3.40681
CU	37.80	82.20	-	1.70342

Cost data

Cost of heat transfer area A (m^2), \$ = 1 456.3$A^{0.6}$

Annual rate of return δ = 0.1

Cooling water cost, \$/(kW.yr) = 17.9

Steam cost, \$/(kW.yr) = 43.55

Problem 4: 4SP2

Stream	T_s (°C)	T_t (°C)	F_{cp} (kW/°C)	h ($kWm^{-2}(°C)^{-1}$)
H1	260.0	43.3	10.55	1.70342
H2	221.1	110.0	26.37	1.70342
H3	204.4	43.3	15.82	1.70342
C1	-3.89	215.6	36.91	1.70342
HU	282.22	282.22	-	3.40681
CU	37.80	82.20	-	1.70342

Cost data

Cost of heat transfer area A (m^2), \$ = 1 456.3$A^{0.6}$

Annual rate of return δ = 0.1

Cooling water cost, \$/(kW.yr) = 17.9

Steam cost, \$/(kW.yr) = 37.26

Problem 5: 4TC2

Stream	T_s (°C)	T_t (°C)	F_{cp} (kW/°C)	h ($kWm^{-2}(°C)^{-1}$)
H1	180	40	2.0	2.00
H2	150	40	4.0	2.00
C1	60	180	3.0	2.00
C2	30	130	2.6	2.00
HU	258.00	258.00	-	1.20
CU	30.00	80.00	-	2.00

Cost data

Cost of heat transfer area A (m^2), \$ = $3000A^{0.5}$

Annual rate of return δ = 0.1

Cooling water cost, \$/(kW.yr) = 21.49

Steam cost, \$/(kW.yr) = 109.55

Problem 6: 4YEE1

Stream	T_s (°C)	T_t (°C)	F_{cp} ($kW°C^{-1}$)	h ($kWm^{-2}(°C)^{-1}$)
H1	150	60	20	0.10
H2	90	60	80	0.10
C1	20	125	25	0.10
C2	25	100	30	0.10
HU	180	180	-	0.10
CU	10	15	-	0.10

Cost data

U = 0.05 (kWm^{-2} $(°C)^{-1}$) for all matches

Cost = $8600+670[\text{area } (m^2)]^{0.83}$ for all exchangers

Hot utility cost = 80 \$/(kW.yr)

Cold utility cost= 20 \$/(kW.yr)

Problem 7: 4YEE2

Stream	T_s (K)	T_t (K)	F_{cp} (kW K^{-1})	h (kW$m^{-2}K^{-1}$)
H1	395	343	4	2.0
H2	405	288	6	0.2
C1	293	493	5	2.0
C2	353	383	10	0.2
HU	520	520	-	2.0
CU	278	288	-	2.0

Cost data:

Cost = 100[area (m^2)] for all exchangers

Hot utility cost = 80 $/(kW.yr)

Cold utility cost= 20 $/(kW.yr)

Rate of return = 1.0

Problem 8: 4YEE3

Stream	T_s (K)	T_t (K)	F_{cp} (kWK^{-1})	h (kW$m^{-2}K^{-1}$)	Cost ($kW^{-1} yr^{-}
H1	443	333	30	1.6	-
H2	423	303	15	1.6	-
C1	293	408	20	1.6	-
C2	353	413	40	1.6	-
S1	450	450	-	4.8	80
W1	293	313	-	1.6	20

Cost data:

U = 0.8 (kW$m^{-2}K^{-1}$) for all matches except ones involving steam.

U = 1.2 (kW$m^{-2}K^{-1}$) for matches involving steam.

Annual cost = 1000 x [area(m^2)]$^{0.6}$ for all exchangers except heaters.

Annual cost = 1200 x [area(m^2)]$^{0.6}$ for heaters

Problem 9: 4FRAS

Streams	T_s (°C)	T_t.(°C)	F_{cp} (kW/°C)	h ($kWm^{-2}(°C)^{-1}$)
H1	250	120	1.5	2.0
H2	150	40	3.0	2.0
C1	30	120	1.0	2.0
C2	70	180	5.0	2.0
Utilities			Cost (\$/kW.year)	
steam	200	200	77.5	2.0
cooling water	20	45	18.8	2.0

Cost data

Exchanger costs (\$) = $6480A^{0.65}$

Annual capital recovery factor = 0.2

Minimum approach temperature = 10°C

Heat transfer coefficient = 1 kW/(m^2 .K)for all streams and utilities

Problem 10: 5SP1

Stream	T_s (°C)	T_t (°C)	F_{cp} (kW/°C)	h (kWm^{-2}(°C)
H1	248.9	121.1	16.62	1.70342
H2	204.4	65.6	13.29	1.70342
C1	37.8	204.4	11.39	1.70342
C2	65.6	182.2	12.92	1.70342
C3	93.3	204.4	13.03	1.70342
HU	235.60	235.60	-	3.40681
CU	37.80	82.20	-	1.70342

Cost data

Cost of heat transfer area A (m^2), \$ = 1 $456.3A^{0.6}$

Annual rate of return δ = 0.1

Cooling water cost, \$/(kW.yr) = 18.16

Steam cost, \$/(kW.yr) = 37.79

Problem 11: 5ZHU

Stream	T_s (°C)	T_t (°C)	F_{cp} (kWK^{-1})	h ($Wm^{-2}K^{-1}$)
H1	159	77	2.285	100
H2	267	80	0.204	40
H3	343	90	0.538	500
C1	26	127	0.933	10
C2	118	265	1.961	500
Steam	300	300	-	50
Water	20	60	-	200

Cost data

Installed heat exchanger cost: cost ($) = $3800 + 750A^{0.83}$

where A = exchanger area (m^2)

Plant life time = 6 yr

Rate of interest = 10% per annum

Cost of hot utility = 110 $/(kW.yr)

Cost of cold utility = 10 $/(kW/yr)

Problem 12:6SP1

Stream	T_s (°C)	T_t (°C)	F_{cp} (kW/°C)	h ($kWm^{-2}K^{-1}$)
H1	226.7	65.6	14.77	1.70342
H2	271.1	148.9	12.55	1.70342
H3	198.9	65.6	17.72	1.70342
C1	37.8	221.1	8.44	1.70342
C2	82.2	176.7	17.28	1.70342
C3	93.3	204.4	13.90	1.70342
HU	235.60	235.60	-	3.40681
CU	37.80	82.20	-	1.70342

Cost data

Steam = $37.26/(kW.yr)

Cooling water = $17.90/(kW.yr)

Annual rate of return = 0.1

Exchanger cost = $1456.3A^{0.6}$

Problem 13: 6YEE

Stream	T_s (K)	T_t (K)	F_{cp} (kWK^{-1})	h ($kWm^{-2}K^{-1}$)
H1	500	320	6	2.00
H2	480	380	4	2.00
H3	460	360	6	2.00
H4	380	360	20	2.00
H5	380	320	12	2.00
C1	290	660	18	2.00
S1	700	700	-	2.00
W1	300	320	-	2.00

Cost data

U = 1 ($kWm^{-2}K^{-1}$) for all matches

Cost of hot utility = \$140/(kW.yr)

Cost of cold utility = \$10/(kW.yr)

Annual cost = 1200 x [area(m^2)]$^{0.6}$ for all exchangers.

Problem 14: 7SP1

Stream	T_s (°C)	T_t (°C)	F_{cp} (kW/°C)	h ($kWm^{-2}K^{-1}$)
H1	226.7	65.6	14.77	1.70342
H2	271.1	148.9	12.55	1.70342
H3	198.9	65.6	17.72	1.70342
C1	37.8	221.1	8.44	1.70342
C2	82.2	176.7	17.28	1.70342
C3	93.3	204.4	13.90	1.70342
C4	176.7	210.0	9.94	1.70342
Steam	235.6	235.6	-	3.40681
Water	37.8	82.2	-	1.70342

Cost data

Cost of heat transfer area A (m^2), \$ = 1 456.3$A^{0.6}$

Annual rate of return δ = 0.1

Cooling water cost, \$/(kW.yr) = 18.16

Steam cost, \$/(kW.yr) = 37.79

Problem 15: 7CIR

Stream	T_s (°C)	T_t (°C)	F_{cp} (kWK^{-1})	h ($kWm^{-2}K^{-1}$)
H1	160	110	7.032	1.60
H2	249	138	8.44	1.60
H3	227	106	11.816	1.60
H4	271	146	7.0	1.60
C1	96	160	9.144	1.60
C2	115	217	7.296	1.60
C3	140	250	18.0	1.60
S	300	300	-	1.60
CW	70	90	-	1.60

U = 0.8 ($kWm^{-2}K^{-1}$)

Cost data

Steam = 80 $\$kW^{-1}yr^{-1}$

Cooling water = 20 $\$kW^{-1}yr^{-1}$

Exchangers = $1300A^{0.6}\ yr^{-1}$

Problem 16: 7FRAS1

Stream	T_s (°C)	T_t (°C)	F_{cp} (kW/°C)	ΔH (kW)	h (kW/(m^2.K)
H1	299	45	86.0	21844.0	0.50
H2	249	70	21.4	3830.6	0.55
H3	160	15	23.5	3407.5	0.60
H4	160	130	129.4	3882.0	0.50
H5	182	75	11.5	1230.5	0.65
C1	200	220	184.7	3694.0	0.45
C2	30	320	147.9	42891.0	0.40
Utilities			Cost ,£/kW.yr		
Gas Turbine Exhaust	515	300	19.253		0.1
HP Steam	250	249	77.994		1.0
IP Steam	200	199	48.006		1.0
Cooling water	15	25	8.994		0.6
Chilled water	5	6	55.440		0.6

Problem 16: 4FRAS1 (continued)

Cost data

Exchanger cost (£) = 1 500 000 + 142A (for A in m^2)

Annual capital recovery factor = 0.6667

Minimum approach temperature = 10°C

Problem 17: 7FRAS2

Stream	T_s (°C)	T_t (°C)	F_{cp} (kW/°C)	ΔH (kW)	h (kW/(m^2.K)
H1	299	45	86.0	21844.0	0.50
H2	249	70	21.4	3830.6	0.55
H3	160	15	23.5	3407.5	0.60
H4	160	130	129.4	3882.0	0.50
H5	182	75	11.5	1230.5	0.65
C1	200	220	184.7	3694.0	0.45
C2	30	320	147.9	42891.0	0.40
Utilities			Cost ,£/kW.yr		
Flue Gas	800	300	170.000		0.5
HP Steam	250	249	77.994		1.0
IP Steam	200	199	48.006		1.0
Cooling water	15	25	8.994		0.6
Chilled water	5	6	55.440		0.6

Cost data

Exchanger cost (£) = 9 500$A^{0.47}$ (for A in m^2)

Annual capital recovery factor = 0.6667

Minimum approach temperature = 10°C

Problem 18: 7YEE

Stream	T_s (K)	T_t (K)	F_{cp} (kWK^{-1})	h ($kWm^{-2}K^{-1}$)
H1	626	586	9.802	1.25
H2	620	519	2.931	0.05
H3	528	353	6.161	3.20
C1	497	613	7.179	0.65
C2	389	576	0.641	0.25
C3	326	386	7.627	0.33
C4	313	566	1.690	3.20
HU	650	650	-	3.50
CU	293	308	-	3.50

Cost data

Cost = 8 600 + 670 x [area (m^2)]$^{0.83}$ for all exchangers

Cost of hot utility = $80/(kW.yr)

Cost of cold utility = $20/(kW.yr)

Problem 19: 9ZHU

Stream	T_s (K)	T_t (K)	F_{cp} (kWK^{-1})	h ($kWm^{-2}K^{-1}$)
H1	327	40	100	0.50
H2	220	160	160	0.40
H3	220	60	60	0.14
H4	160	45	400	0.30
C1	100	300	100	0.35
C2	35	164	70	0.70
C3	85	138	350	0.50
C4	60	170	60	0.14
C5	140	300	200	0.60
Hot oil	330	250	-	0.50
Water	15	30	-	0.50

Problem 19: 9ZHU (continued)

Cost data

Exchanger cost	= 10 000 + 350 x Area (m^2)
Plant life time	= 5 (yr)
Rate of interest	= 0 (%)
Annual cost of hot oil	= 60 ($\$kW^{-1}annum^{-1}$)
Annual cost of cooling water	= 6 ($\$kW^{-1}annum^{-1}$)

Problem 20: 9AHM

Stream	Material of construction	T_s (°C)	T_t (°C)	F_{cp}	h ($kWm^{-2}K^{-1}$)
H1	CS	120	65	25	0.50
H2	CS	80	50	150	0.25
H3	SS	135	110	145	0.30
H4	SS	220	95	10	0.18
H5	CS	135	105	130	0.25
C1	TI	65	90	75	0.27
C2	CS	75	200	70	0.25
C3	CS	30	210	50	0.15
C4	TI	60	140	25	0.45
Steam	-	250	249	-	0.35
Cooling water	-	15	16	-	0.20

Installed shell/tube heat exchanger cost laws for different materials of construction

Material	Symbol	Cost, $
Carbon steel	CS	30 800 + $750A^{0.81}$
Stainless steel	SS	30 800 + $1644A^{0.81}$
Stainless and carbon steel	CS/SS or SS/CS	30 800 + $1339A^{0.81}$
Titanium	TI	30 800 + $4407A^{0.81}$
Carbon steel and titanium	CS/TI or TI/CS	30 800 + $3349A^{0.81}$
Stainless steel and titanium	SS/TI or TI/SS	30 800 + $3749A^{0.81}$

Problem 19: 9AHM (continued)

Cost data

Plant life = 6 years

Capital interest = 10% per annum

Cost of hot utility = 110 (\$/(kW.yr))

Cost of cold utility = 10 (\$/(kW.yr))

Problem 21: 9JEG2

Stream	T_s (°C)	T_t (°C)	F_{cp} (kW(°C)$^{-1}$)	Exchanger specification
H1	327	45	100	Shell-and-tube (SS)
H2	220	160	180	Shell-and-tube (CS)
H3	220	60	60	Shell-and-tube (CS)
H4	160	45	400	Spiral (CS)
C1	100	300	100	Shell-and-tube (CS)
C2	35	164	70	Plate-and-frame (CS)
C3	85	138	350	Spiral (CS)
C4	60	170	60	Shell-and-tube (SS)
C5	140	300	200	Shell-and-tube (TI)
HU	360	-		Shell-and-tube (CS)
CU	10	-		Shell-and-tube (CS)

Exchanger classification table

	H1	H2	H3	H4	Steam
C1	$_{5.5}G5^{0.65}$	$_{5.0}G3^{0.5}$	$_{5.0}G3^{2.0}$	$_{7.0}G1^{0.40}$	$_{5.0}G3^{0.50}$
C2	$_{1.0}G2^{0.90}$	$_{1.0}G2^{0.75}$	$_{1.0}G2^{2.3}$	$_{1.4}G1^{0.4}$	$_{1.0}G2^{0.6}$
C3	$_{0.50}G1^{1.1}$	$_{0.50}G1^{0.85}$	$_{0.50}G1^{2.6}$	$_{0.50}G1^{0.40}$	$_{0.50}G1^{0.70}$
C4	$_{0.20}G4^{0.80}$	$_{0.15}G5^{0.50}$	$_{0.15}G5^{2.2}$	$_{0.26}G1^{0.40}$	$_{0.15}G5^{0.55}$
C5	$_{0.75}G7^{0.85}$	$_{0.65}G6^{0.67}$	$_{0.65}G6^{2.4}$	$_{1.1}G1^{0.40}$	$_{0.65}G6^{0.60}$
Cooling water	$_{0.60}G5^{0.65}$	$_{0.50}G3^{0.50}$	$_{0.50}G3^{2.0}$	$_{0.70}G1^{0.40}$	-

Problem 20: 9AHM (continued)

Cost data

Plant life	= 6 years
Capital interest	= 10% per annum
Cost of hot utility	= 110 (\$/(kW.yr))
Cost of cold utility	= 10 (\$/(kW.yr))

Problem 21: 9JEG1

Stream	T_s (°C)	T_t (°C)	F_{cp} (kW(°C)$^-$	h (kWm^{-2} °C$^-$	Exchanger specification
H1	327	45	100	0.80	Shell-and-tube (SS)
H2	220	160	180	0.50	Shell-and-tube (CS)
H3	220	60	60	2.00	Shell-and-tube (CS)
H4	160	45	400	0.40	Spiral (CS)
C1	100	300	100	5.00	Shell-and-tube (CS)
C2	35	164	70	1.00	Plate-and-frame (CS)
C3	85	138	350	0.50	Spiral (CS)
C4	60	170	60	0.20	Shell-and-tube (SS)
C5	140	300	200	0.80	Shell-and-tube (TI)
HU	360	-		0.50	Shell-and-tube (CS)
CU	10	-		0.50	Shell-and-tube (CS)

Exchanger classification table

	H1	H2	H3	H4	Steam
C1	G5	G3	G3	G1	G3
C2	G2	G2	G2	G1	G2
C3	G1	G1	G1	G1	G1
C4	G4	G5	G5	G1	G5
C5	G7	G6	G6	G1	G6
Cooling water	G5	G3	G3	G1	-

Key

Spiral exchanger : G1 $\rightarrow$ CS/CS

Plate-and-frame : G2 $\rightarrow$ CS/CS

Shell-and-tube exchanger: G3 $\rightarrow$ CS/CS

: G4 $\rightarrow$ SS/SS

: G5 $\rightarrow$ CS/SS

: G6 $\rightarrow$ CS/TI

: G7 $\rightarrow$ SS/TI

: G8 $\rightarrow$ TI/TI

Notes

A few statements will make interpretation of the match-dependent heat transfer coefficients in the exchanger classification table easier. According to Jegede and Polley (1992):

> For a match between hot stream 1 and cold stream 5, a shell-and-tube heat exchanger made of a mixture of carbon steel and stainless steel is required. Stream 1 has an *h*-value of 0.65 $kWm^{-2}\ °C^{-1}$ while stream 5 has an *h*- value of 5.5 $kWm^{-2}\ °C^{-1}$. On the other hand, for a match between stream 1 and cold stream 7, a spiral heat exchanger (made of carbon steel) is required. Stream 1 has an *h*-value of 1.1 $kWm^{-2}\ °C^{-1}$ and stream 7 has an *h*-value of 0.5 $kWm^{-2}\ °C^{-1}$.

This problem is an example of a situation in which the film coefficients of the streams are match-dependent.

Cost data

Exchanger Specification	Capital cost (£)
G1	$19\ 687A^{0.59}$
G2	$1\ 905A^{0.78}$
G3	$19\ 600 + 1\ 008A^{0.81}$
G4	$28\ 000 + 907A^{0.91}$
G5	$23\ 800 + 1\ 145A^{0.85}$
G6	$34\ 300 + 1\ 719A^{0.92}$
G7	$38\ 000 + 1\ 850A^{0.92}$
G8	$49\ 000 + 1\ 957A^{0.93}$

Plant life : 5 years

Rate of interest : 10%

Cost of hot utility : 110 (£$kW^{-1}yr^{-1}$)

Cost of cold utility : 10 (£$kW^{-1}yr^{-1}$)

Notation

CS = Carbon steel; SS = Stainless steel; TI = Titanium.

Problem 22: 10BYF

Stream	T_s (°C)	T_t (°C)	h ($kWm^{-2}K^{-1}$)	Material	Multiple ($/year)	Flux (kW/(°C))
H1	360	220	0.50	1.00	0	20.0
H2	330	50	0.70	2.00	0	12.0
H3	200	70	0.90	1.00	0	4.0
H4	190	30	0.10	1.00	20 000	16.0
H5	150	40	1.00	1.00	0	10.0
C1	30	120	0.20	4.00	0	10.0
C2	10	230	0.10	1.00	0	18.0
C3	110	325	0.50	1.00	0	12.0
C4	80	310	0.40	1.50	20 000	6.0
C5	40	150	2.00	1.80	0	20.0
Utility	T_s (°C)	T_t (°C)	h ($kWm^{-2}K^{-1}$)	Material	Cost ($/(kW.yr)	
CW	20	30	0.30	1.00	15	-
Steam	340	340	0.30	1.00	100	-
Exchangers = 1 000$A^{0.6}$ $/year						

Problem 23: 10SP1

Stream	T_s (°C)	T_t (°C)	F_{cp} (kW/°C)	h ($kWm^{-2}K^{-1}$)
H1	160.0	93.3	8.79	1.70342
H2	248.9	137.8	10.55	1.70342
H3	226.7	65.6	14.77	1.70342
H4	271.1	148.9	12.55	1.70342
H5	198.9	65.6	17.72	1.70342
C1	60.0	160.0	7.62	1.70342
C2	115.6	221.7	6.08	1.70342
C3	37.8	221.1	8.44	1.70342
C4	82.2	176.7	17.28	1.70342
C5	93.3	204.4	13.90	1.70342
Steam	235.6	235.6	-	3.40681
Water	37.8	82.2	-	1.70342

Cost data

Steam = \$37.26/(kW.yr)

Cooling water = \$17.90/(kW.yr)

Annual rate of return = 0.1

Exchanger cost = $1456.3A^{0.6}$

The specifications of design data for the SP series of problems, as given by Liu (1987) are shown in Table E.1. The SP series of problems is 3SP3, 4SP1, 4SP2, 5SP1, 6SP1, 7SP1, and 10SP1.

Table E.1: Specifications of design data for the SP series of problems.

	4SP1	Others
Steam		
Pressure, kPa	6635	3102
Latent heat, kJ/kg	1527.17	1785.11
Temperature, °C	282.22	235.6
Cooling water		
Temperature, °C	37.8	37.8
Heat capacity, kJ/kg-K	4.1840	4.1840
Maximum water output temperature, °C	82.2	82.2
Maximum allowable approach temperature, °C:		
Heat exchanger	11.1	11.1
Steam heater	13.9	13.9
Water cooler	11.1	11.1
Overall heat-transfer coefficients, W/m^2-K:		
Heat exchanger	851.71	851.71
Steam heater	1135.61	1135.61
Water cooler	851.71	851.71
Equipment downtime (hr/yr)	380	380
Cost of heat-transfer area A (m^2) ($)	1 456.3 $A^{0.6}$	1 456.3 $A^{0.6}$
Annual rate of return, δ	0.1	0.1
Cooling-water cost, $/kg	1.1023×10^{-4}	1.1023×10^{-4}
Steam cost, $/kg	2.2046×10^{-3}	2.2046×10^{-3}