A RECURSIVE DESIGN METHOD

FOR

HEAT EXCHANGER NETWORKS

by

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CERTIFICATE OF ORIGINALITY

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ABSTRACT

Over the past two decades, considerable progress has been achieved in the energy integration problem. In spite of these efforts, limitations and drawbacks still exist in the current methods.

Mathematical programming methods, which formulate the heat exchanger network problem as a non-linear optimisation problem, are limited by available solvers such as GAMS. Sometimes it is difficult to achieve a global solution, particularly when the HEN problem size exceeds 10 streams. By contrast, a typical industrial problem normally consists of about 30-80 streams. This severely limits the application of mathematical programming methods in many instances.

Evolutionary methods such as Pinch Design Method have been successfully applied to industrial-scale heat exchanger network synthesis. However, the methods are more concerned with targeting rather than detailed design. These methods still encounter problems. For example, commencing a design from a MER design may lead to a very complex system which is sometimes difficult to evolve to the cost optimal design. As well, heuristic rules, which guide the match selection, may not achieve the desired objective and many alternatives may have to be explored. For a large problem, such an exhaustive search may be quite cumbersome. Finally, the cost laws associated with the problem are not incorporated into the match selection procedure until the final stages. The objectives of the design optimisation are the physical parameters: area, number of units and utility, rather than the cost. Consequently the trade-off between operating and capital investment is sometimes poorly addressed. These disadvantages may make it difficult to achieve a high quality design, especially for a large industrial scale problem.

In this study, a novel and reliable method for heat exchanger network synthesis is proposed. The prime objective of this work has been the elimination or reduction of drawbacks inherent in both evolutionary methods and mathematical programming methods whilst retaining the advantages of both methods.

This method is based on a new decomposition strategy coupled with a new match selection model and procedure for detailed design.

In this new method, decomposition for the problem is represented by a binary tree. First, the problem is treated as a root or parent entity. An index called the dominant cost component of the total annual cost is proposed and used to determine if further decomposition of the node is required (including the root node). If decomposition for the node is required, the node will be decomposed into two sub-nodes or child nodes. Each child node may be further subdivided until the solution is reduced.

Using the proposed binary tree decomposition strategy, the algorithm readily handles problems with considerably different film heat-transfer coefficients as well as problems with equal transfer coefficients whilst applying a consistent set of rules.

During the detailed design' stage, a new match selection method is used. It is based on a match selection model, derived from a simplified superstructure involving no interaction between individual matches. This match selection procedure builds the backbone of the design by finding an initial design. This method also provides a systematic design method for the parts of the streams distant from the pinch or partition temperatures.

The proposed match selection method significantly reduces the difficulties inherent in the heuristic rules proposed for match selection in the Pinch Design Method. The final design depends on the method itself rather than on the designer's bias as the rules are consistently applied.

To overcome the inaccuracies in trade-off between utility cost and capital cost in the evolutionary method, two optimisations, individual match cost optimisation and partition temperature optimisation, are undertaken at various steps in the design. Fortunately, these trade-offs do not require complex programming.

The new method is not sensitive to the size of the problem. It easily handles a variety of difficult situations, such as forbidden matches or imposed matches. Hence, safety consideration and layout constraints may be easily incorporated into the design.

The design method can also easily be extended into more detailed design. For example, if the costs and layout of the units are available, piping cost, power cost for pumping and cost for valves may be incorporated into the cost for an individual match right from the start.

An application of the new method to practical problem is demonstrated by case studies. One of the case studies is the well-known industrial scale Aromatics Plant. Designs from the new method are compared to the designs proposed by other researchers. The case studies confirm that the proposed method can achieve similar or better design quality. However, the design effort is significantly reduced.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

Global warming concerns and increased competition have caused energy consumption and greenhouse gas emissions to become major concerns for government and industry world-wide, particularly for the major energy consumption industries, such as, chemical, petrochemical and power industries. Efficient energy management not only increases companies' competitive advantages by reducing costs but it also protects our environment by diminished greenhouse-gas emission.

One of the energy management technologies widely exploited in the process industries is heat exchanger network synthesis. Although significant progress has been achieved since work commenced in 1965, a number of disadvantages are still encountered in the existing design methods. For example, the process of network evolution is a key process step in the Pinch Design Method. However, it is sometimes difficult to implement in practice and the final design quality may suffer if the initial design is poorly chosen.

1.1 Heat Exchanger Networks

In a typical chemical or petrochemical plant, process units normally operate at fixed operating conditions, such as a fixed range of temperatures and pressures. To meet these design objectives, cold streams need to be heated to their target temperatures and hot streams need to be cooled to their target temperatures. To achieve these targets, energy is added to or removed from cold or hot streams, respectively. This process is normally undertaken in heat exchanger networks (HEN), where process heat exchangers, heaters and coolers are employed to transfer energy between hot and cold process streams, and between process streams and utilities.

The objective of heat exchanger network synthesis is to discover a design with the minimum total cost. This design must be robust, flexible and controllable.

The total cost for a network is composed of the operating cost and the capital cost. Operating cost is determined by the amount of utilities consumed in the network whilst capital cost depends on the cost of units which constitute the heat exchanger network and the interest rate. There is a classical relationship between these costs. Usually, if more utilities are consumed by the network, the lower the capital cost. However, reduction in energy costs will result in an increase of the capital cost. Hence, the minimum total cost is consequence of a trade off between the utility cost and the capital cost.

Unfortunately, heat exchanger network design is a combinatorial problem as a very large number of alternative designs exist. It has been reported that, a problem with M hot streams and N cold streams might have (M×N)! different designs (Ponton and Donaldson, 1974). For a problem with eight streams, a total of 2.3×10^{87} possible designs has been suggested (Linnhoff, 1979). To discover the cost optimal design amongst so many possible alternative designs is an exceedingly difficult task without systematic methods which enable the designer to identify those combinations achieving optimal (or near–optimal) design.

1.2 Existing Synthesis Methods

The methods of heat exchanger network synthesis fall into two categories: evolutionary methods and mathematical programming methods.

1.2.1 Evolutionary Methods

The best-known evolutionary method is the Pinch Design Method. It is based on an energy recovery "bottleneck" identified by Hohmann (1971). Extending the concepts of Pinch Technology, the designer can devise simple targets to guide the design, narrow the design space and account for operability, plant layout, safety consideration to drive the design towards solutions which are thermally efficient and industrially acceptable. The contribution of "Pinch Technology" is believed to lie in the "analysis" rather than the design (Linnhoff, 1993).

The Pinch Design Method normally decomposes the system into two sub-systems, one above and one below the pinch. Each sub-system is considered separately. For each sub-system, a network is designed to achieve the maximum energy recovery design (MER). This MER design is evolved to reduce the total area while attempting to approach a minimum unit design. The MER designs often possess a complex topology very different from the topology of a cost optimal design. This difference may cause problems when the designer attempts to evolve the MER design to the cost optimal design.

Several tools, such as "The Driving Force Plot" and "The Remaining Problem Analysis", have been developed to guide match selection. They provide very useful guidelines. Unfortunately, these heuristic rules are insufficient and their application cannot guarantee an optimal design. As well, the heuristics may prove contradictory in some instances and this introduces uncertainty and difficulty into match selection. Usually, the final solution depends, to some extent, on the designer's bias and the quality of the design may not be guaranteed. When a problem is large, match selection becomes much more complex and quality for the design is more difficult to be guaranteed.

Inaccurate trade-offs between the operating and capital costs may also introduce quality problems in the Pinch Design Method. Two causes may be identified. First, when matches are selected, the selection criteria are based on physical parameters such as total area and utility consumption rather than the total annual cost. Second, the capital cost and utility cost can not be considered simultaneously.

1.2.2 Mathematical Programming Methods

Mathematical programming methods describe the heat exchanger network problem as a mathematical optimisation problem. These mathematical models are then solved by a mathematical programming algorithm such as MILP (mixed integer linear programming) and MINLP (mixed integer non-linear programming). In order to formulate the mathematical models, a topology and a matching pattern are assumed prior to the design. The design stage is a classical optimisation based on a fixed pattern of matching. The best-known topology and match pattern is the so called superstructure proposed by Yee and Grossmann (1990).

Mathematical programming solvers severely limit the applicability of such methods. The problem may converge to local optima. However, the fatal disadvantage of these methods is that the solvers usually experience difficulty in solving problems which exceed 10 streams. Unfortunately, the normal number of streams in industrial problem is of the order of 30-80 streams (Kravanja et. al.1997, Gundersen et. al. 1988). The remaining disadvantage of the methods results from uncertainties in the topology and match pattern for the system. The topology and match pattern may not be sufficiently general to cover all possible alternatives. For example, the number of stages in the superstructure required for the design is unknown. It is determined by trial and error. This may mean that the optimal design may not be included in the proposed topology and match pattern.

1.3 Objectives and Methodology of This Work

The objectives of this research have been to develop a simple but practical method for heat exchanger network synthesis which is a hybrid but combines the advantages of both thermodynamic and mathematical programming methods and at the same time overcomes some of their disadvantages. The new method should be readily understood and easily implemented. As well, it should be capable of producing high quality designs for industrial sized problems.

The objectives of this research are briefly summarised:

- To develop a match selection method to overcome or decrease the uncertainty and difficulty in the match section procedure of Pinch Design Method.

- To develop optimisation strategies which overcome or reduce the inaccurately accounted for trade-off between capital cost and utility cost and hence improve the design quality.

- To develop a general method which is not sensitive to different film heat transfer coefficients for the streams.

- To develop a method which is capable of handling problems with constraints resulting from operability, plant layout or safety considerations.

- To develop a method which achieves an optimal design without using complex programming algorithms (or tools) and is not sensitive to the size of the problem.

1.4 Thesis Organisation

This thesis is organised into the following six chapters.

Chapter 1 provides a brief introduction to the problem considered.

Chapter 2 reviews the main methods for heat exchanger network synthesis. The methods are categorised into two main groups: evolutionary and mathematical programming methods. The advantages and disadvantages of existing methods are critically analysed.

Chapter 3 presents a new decomposition strategy called binary-tree decomposition. An index called the dominant cost component is proposed and used to determine whether decomposition for a node is required or not.

Chapter 4 presents a match selection method developed in this research. The new match selection method is based on a simplified superstructure, cost optimal individual matches and a match selection model.

Chapter 5 presents a recursive design method for heat exchanger network synthesis based on the new binary tree decomposition strategy and the proposed match selection method. To correct for inaccuracies in the trade-off between capital and energy costs resulting from the lack of interaction inherent in the simplified superstructure, a partition temperature optimisation is performed. Several case studies are included to demonstrate all facets of the new method. Designs from this method are compared with the designs by presently available methods (e.g. Pinch Design and mathematical programming). In general, the resulting designs are comparable to or of lower cost than those of existing workers

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The synthesis of heat exchanger networks has been studied since the 1960s. Numerous papers have been published on the problem and significant progress has been achieved. The synthesis of heat exchanger network is undoubtedly the most mature synthesis technique in process engineering.

Excellent reviews of the developments in this area have been provided by Nishida et al.(1981), Gundersen and Naess (1988), Linnhoff (1993), Zhu (1994) and Jezowski (1994 a, b). In this chapter, a detailed discussion of the principal methods which represent current state of the art for heat exchanger network synthesis is presented. The problems inherent in existing methods are identified.

2.2 A Statement of the Heat Exchanger Network Problem

The synthesis of heat exchanger networks (HEN) was introduced to scientific literature in the early 60s (Westbrook 1961, Hwa, 1965). A statement of the heat exchanger network synthesis problem is (Yee and Grossmann 1990) :

Given are a set of hot process streams to be cooled and a set of cold streams to be heated. Specified are also each hot and cold stream's heat capacity flow rates and the initial and target temperatures stated as either exact values or inequalities. Given also are a set of hot utilities and a set of cold utilities and their corresponding temperatures. The objective then is to determine the heat exchanger network with the lowest annual cost. The solution defines the network by providing the following:

1. Utilities required.
2. Stream matches and the number of units.
3. Heat loads and operating temperatures of each exchanger.
4. Network configuration and flows for all branches.
5. Area for each exchanger.

The basic objective of the heat exchanger network is to meet the requirement of the process. This is not a difficult task without economic concerns. However, reduced investment and lower energy consumption are required in industry due to increased competition and environment awareness.

The goals of reducing capital investment and lower energy consumption can not be achieved simultaneously. Normally, a design featuring low capital investment consumes more energy and conversely a design with low energy consumption requires more capital investment. The optimal design is obviously achieved by trading-off energy consumption with capital investment. Hence, heat exchanger network synthesis fundamentally is an optimisation problem.

The dominant feature of the synthesis problem is determining the best topology for the system. This search for the best connectivity means that the synthesis of heat exchanger networks differs from the optimisation of operating conditions for an existing system. The synthesis phase is more complicated due to the undecided topology of the system.

In addition to the quantitative objective of the optimal total annual cost, in practice, several qualitative objectives need to be taken into account, such as safety, operability, layout, flexibility, and controllability.

2.3 Problem Analysis -- Targets

The problem analysis in terms of targets such as minimum utility consumption, minimum total area, etc. is a key stage during synthesis of heat exchanger networks. It is performed prior to detailed design by determining targets for utility consumption, total area, the number of the units and costs.

Such targets provide lower bounds for the design problem. Knowing these target values, the designer can determine how close his/her designs are to the targets and hence time is not wasted exploring a large space of alternative solutions for acceptable designs.

Targets usually play an extremely important role in evolutionary methods, such as the Pinch Design Method.

2.3.1 The Energy Target

The energy target provides the minimum utility consumption for a given heat exchanger network.

Hohmann (1971) first proposed a rigorous method to calculate the energy target using a feasibility table. Shortly after Linnhoff and Flower (1978) proposed a method called Problem Table Algorithm (PTA) to calculate this target. Other significant contributions to the field include the TQ diagram (Umeda et al.,1978), HAF (Greenkorn, 1978) and composite curves (Huang and Elshout, 1976). The HAF actually is a grand composite curve. The most widely used tools are Problem Table Algorithm (PTA) and Composite Curves.

Composite Curves:
Composite curves summarise the relationship between temperature and enthalpy for both hot and cold streams (Figure 2.1). All the hot streams and all the cold streams are treated as an entity. Hence, a single composite curve exists for hot stream with a single composite curve for cold streams.

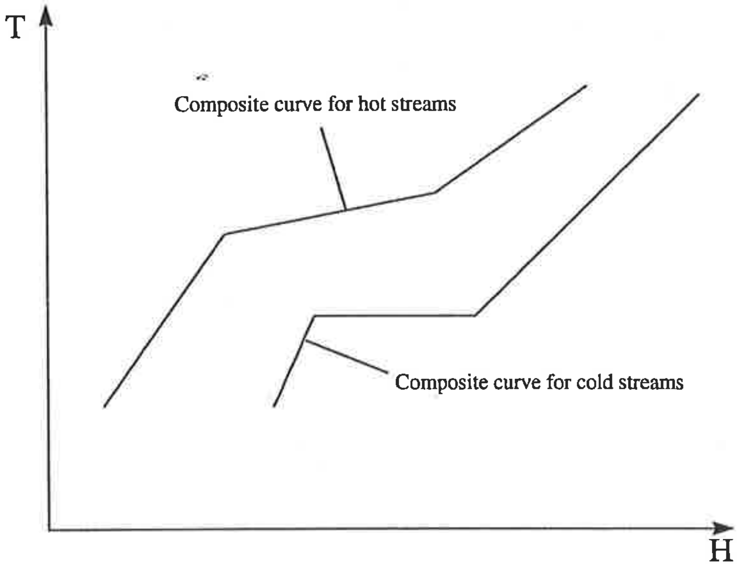


Figure 2.1: Composite curves

The minimum utility consumption for a system depends on the properties of the hot streams and cold streams, and on the value of the minimum temperature approach. Figure 2.2 illustrates the relationships between minimal hot utility consumption, minimal cold utility consumption and the value of the minimum temperature difference ΔT_{min}. As the minimum temperature difference ΔT_{min} changes, the composite curves move horizontally resulting in a change in the value of both minimum hot utility and minimum cold utility consumption.

If a system is constrained by forbidden, restricted or required matches, the problem becomes more complicated. Thermodynamic methods are not available to accurately calculate the energy target. However, the energy target for these situations can be obtained by mathematical programming methods, using the LP transportation model proposed by Cerda et al. (1983) or the LP transhipment model with reduced size proposed by Papoulias and Grossmann (1983).

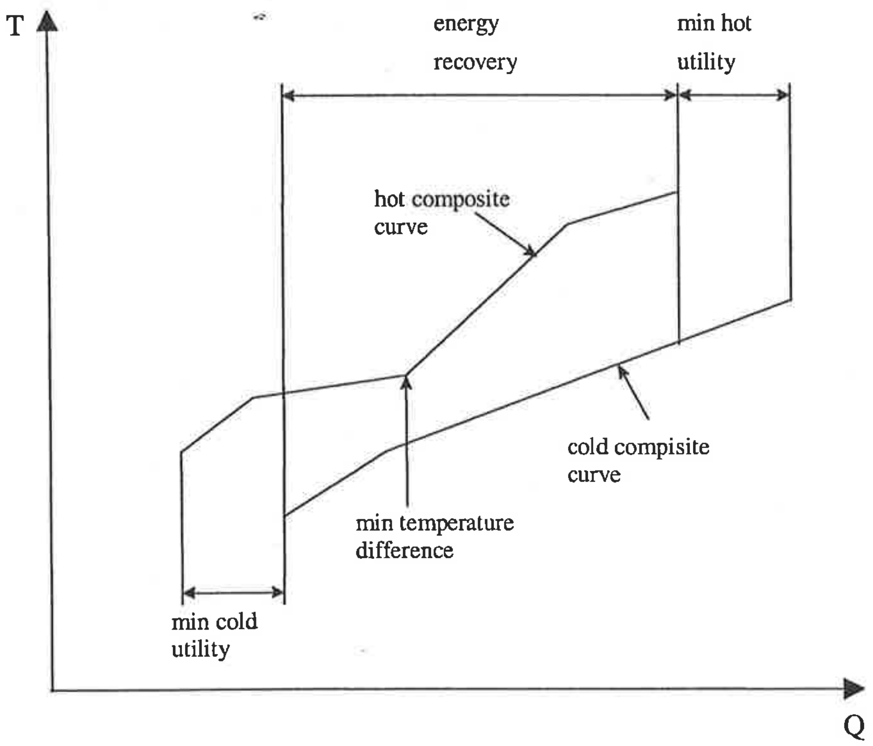


Figure 2.2: The composite curves and energy recovery target

2.3.2 The Area Target

The area target algorithm calculates the minimum total heat transfer area required by a heat exchanger network prior to design. It is useful in setting the lower bound for evolution and estimation of the capital investment.

The total area for a heat exchanger network depends on the network structure. Predicting the area target is more difficult than energy target since the network structure is not available prior to the design. For thermodynamic methods, a simple formula is available to compute the area target. Unfortunately, this formula is only strictly correct if all streams in the system have equal film transfer coefficients. For systems with unequal film transfer coefficients, the thermodynamic method only provides an approximate value for area target. The approximation is normally acceptable.

By contrast, the area target for systems with equal and unequal film coefficients may be solved by mathematical programming methods. However, the area target is a non-linear problem and the search by mathematical programming may fail or locate a local optimal solution particularly when the size of the problem is large.

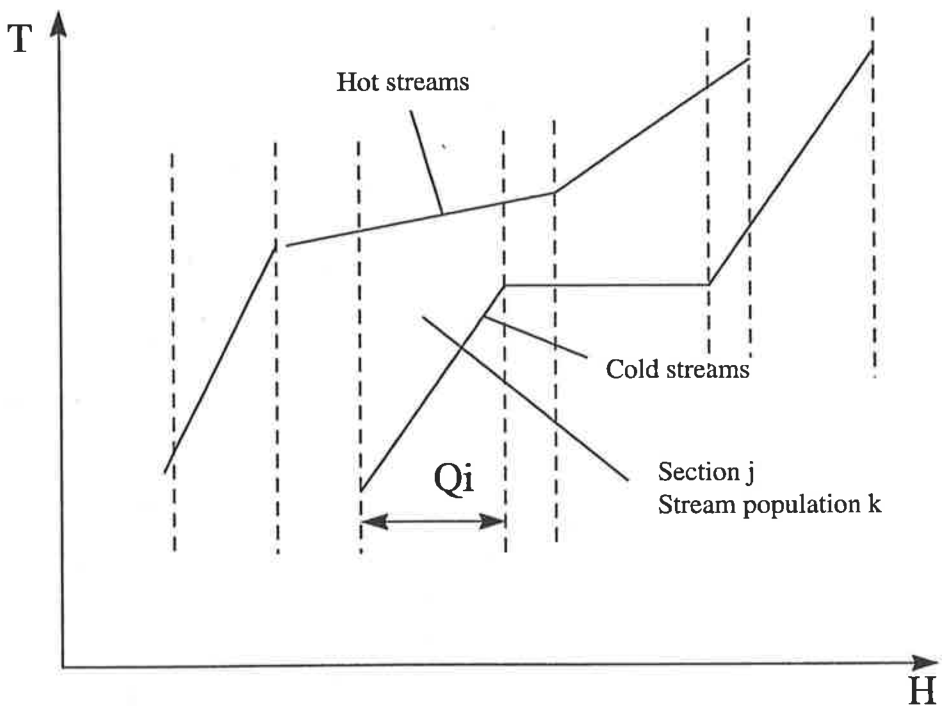


Figure 2.3: Enthalpy intervals for area target calculation

Review:

Hohmann (1971) and Nishida et al. (1971) presented methods to calculate area targets for a system with equal film coefficients. Their methods were subsequently modified by Nishida et al. (1977). The modified method to calculate the area target is summarised by Equation 2.1. In the formula, the film heat transfer coefficients for all streams are identical and all exchangers are assumed purely counter current. The method may also be described by Figure 2.3. In Figure 2.3, the hot and cold composite curves are divided into several sections at the 'kink' points. Within each section, all streams, k, in each interval, j, have to be split and matched vertically. This design achieves the minimal total area and is referred to as a "spaghetti design".

$$A_{\min} = \frac{1}{U} \sum_{j} \frac{Q_j}{\Delta T_{LM_j}} \quad (2.1)$$

Townsend and Linhoff (1984) extended the Equation 2.1 to account for the individual film transfer coefficients of different streams. The extended formula is presented as Equation 2.2. A uniform value of the temperature approach was used and the equation is known as the "Uniform Bath Formula".

$$A_{\min} = \sum_{j} \frac{1}{\Delta T_{LM_j}} \sum_{k} \left[\frac{\Delta q_k}{h_k} \right] \quad (2.2)$$

The Uniform Bath Formula is rigorous only if the overall transfer coefficient is constant for all matches and energy transfer is strictly vertical. When the system has different film transfer coefficients, the formula may be used to approximate the area target. The error resulting from the Bath formula is normally no greater than 10% compared to the value calculated by mathematical programming methods, even when the film transfer coefficients differ by one order of magnitude (Ahmad et al. (1985) and Townsend et al., 1989). However, Saboo et. al. (1986) showed that the Bath formula does not work well for problems whose stream film transfer coefficients are significantly different. It normally overestimates the area target. In spite of such deficiencies, the Uniform Bath Formula is still used as a practical method to estimate the area target.

To deal with the different film transfer coefficients problem, Nishimura et al. (1980) presented a rigorous method which is restricted to the case of a single hot stream in enthalpy balance with many cold streams or a single cold stream in enthalpy balance with many hot streams. Townsend et al. (1989) extended Nishimura's method to an approximate method for the general case by using stream individual ΔT contributions. Rev and Fonyo (1991) proposed an approach called the Diverse Bath Formula, which combined unequal film transfer coefficients and individual stream ΔT contributions to calculate total heat transfer area.

For mathematical programming methods, Saboo et al. (1986) presented an approach to calculate a rigorous target for problems with different heat transfer coefficients. In their method, temperature intervals (TI's) are chosen based on the 'kink points' in the composite curves. TI's are then gradually decreased until the area target is obtained by solving a simple LP transportation model.

Colberg and Morari (1990) developed a NLP model for both the area target and the capital cost target. Their model is based on the temperature intervals and is capable of handling problems involving unequal film transfer coefficients and constrained matches.

Yee et al. (1990) also proposed two NLP models for simultaneous energy and area targeting and for area targeting with a fixed utility requirement using a superstructure. The models are based on stages, which may span several temperature intervals, rather than TI's (temperature intervals). This concept significantly reduces the number of variables in the NLP model. Their method is believed to be more robust and efficient.

2.3.3 The Unit Target

The unit target involves calculation of the minimum number of units in a heat exchanger network.

The concept was introduced with the 'N-1' rule by Hohmann (Hohmann, 1971). Boland and Linnhoff extended Hohmann's N-1 rule (Boland and Linnhoff, 1979). They used Euler's theorem from graph theory to take into account the number of sub-systems and the number of loops. The general formula for unit target is described below:

$$N_u = N_s + N_l - N_p \tag{2.3}$$

where N_u is the number of units, N_s is the number of streams (both process and utilities), N_l is the number of loops, N_p is the number of independent problems or sub-systems.

When calculating the overall unit target, the number of loops N_l is set to zero and the number of independent problems N_p is set to 1. Under such circumstance, the equation 2.3 is simplified to:

$$N_u = N_s - 1 \tag{2.4}$$

Equation 2.4 calculates the minimum number of connections for a graph with N_s nodes. Each node represents a stream and a connection represents a unit. Since the number of the independent problems N_p is set to 1, all nodes should be connected into one network (chain) and no node is separated from the network. This node-connection network does not represent the form of the heat exchanger network. In heat exchanger networks, it is unnecessary to connect all the nodes into one single independent problem (chain). Some nodes may be connected to form an independent chain, and others may form another independent chain and so on. This can be demonstrated by a system with two hot streams and two cold streams. The minimum number of the units for this system is two if no utilities are required. By using equation 2.4, the minimum number of the unit for this 4-stream problem is three or five depending on whether the utilities are included in the number of the streams.

In 1981, Linnhoff and Turner presented a unit target method for the maximum energy recovery (MER) design. The system is divided into two independent problems above and below the pinch, and the 'N-1' rule is applied to the two sub-systems separately.

Since the pinch partition causes some streams to be counted twice, the unit target may be overestimated.

In 1983, Cerda and Westerberg (1983) proposed a MILP transportation model for the unit target. They relaxed the MILP model to a LP model so that the solution of a MILP problem could be avoided. A similar strategy by using MILP transhipment models was proposed by Papoulias and Grossmann (1983). Their methods for the unit target can handle systems with constrained matches and multiple utilities.

2.3.4 The Shell Target

A match in the heat exchanger network may require more than a single shell. The reason may be the use of non-counter current exchangers or a restriction placed on the maximum area for a shell. In fact, if the exchanger is of the non-counter current type (eg. Multiplepass), the number of shells is more important than the number of units for cost estimation (Colbert, 1982 and Hohmann, 1984).

The calculation of a shell target is also based on the composite curves. The minimum number of shells below and above the pinch are calculated. The results for the two sub-systems are added to obtain the total number of shells required by the network.

Shiroko and Umeda (1983) proposed a step-wise graphical procedure to estimate the number of shells from the composite curves. Trivedi et al. (1987) proposed a 'stepping-off' approach on the composite curves which is similar to the McCabe-Thiele construction. The method is very straightforward. However, it appears to be less reliable and may significantly under-predict the required number of shells (Ahmad and Smith, 1989). Johns (1987) presented a method based on the enthalpy 'kinks' intervals on composite. Later, Ahmad and Smith (1989) combined the enthalpy intervals and stream contribution concepts together to target the number of shells. Their method was reported to be more reliable and it has been further modified to take into account streams, area and units by Suaysompol and Wood (1991).

Although the vertical heat transfer model does not guarantee the true minimum value for area targeting, it may yet provide a sufficiently accurate model for shell targeting (Ahmad and Smith, 1989).

2.3.5 Total Annual Cost Target and Supertarget

The total annual cost target consists of the calculation of operating cost and capital cost. The targets available for energy, total area, and the number of the units/shells, enable the utility cost, capital investment and hence the total annual cost to be predicted prior to design. These are the basis of the so-called "Supertarget".

Both energy consumption and the network capital cost for the problem are strongly influenced by the value of the minimum temperature approach. Hence, the right choice of the minimum temperature approach value is vitally important or even critical to the cost of the design.

Prior to the supertarget, the choice of a reasonable value of ΔT_{min} was based on experience, for example, 20K for ambient process or 5K for refrigeration systems (Townsend and Linnhoff 1984). Such a value based on the experience may be reasonable. However, Linnhoff and Ahmad (1986a & b) confirmed that a design starting from a poorly estimated ΔT_{min} may never be evolved to (or near to) the optimal design. This problem is referred to as a 'topology trap'.

To avoid thus trap, a cost-targeting procedure called "Supertargeting" was proposed by Linnhoff and Ahmad. For each ΔT_{min}, the energy target, the area target and the unit target are calculated by the methods outlined earlier. Based on these targets, a total annual cost for this individual ΔT_{min} is obtained. The optimal ΔT_{min} is found by varying the value of the minimum temperature approach (Linnhoff and Ahmad, 1986a & b, 1990 a & b).

As metioned earlier, if the Bath formula is used to calculate the area target, the resulting target may be incorrect. This error could bias the optimal minimum temperature approach. However, Ahmad et al. (1985, 1990) reported that provided that the slope is approximately correct, the optimal ΔT_{min} (HRAT) produced by supertargeting is reasonable.

In fact, total annual cost is less sensitive to minimum temperature approach compared to energy cost and capital cost. The optimum region is normally rather flat. When the minimum temperature approach is close to the optimal value, slight differences in approach values have little impact on the total annual cost (Figure 2.4).

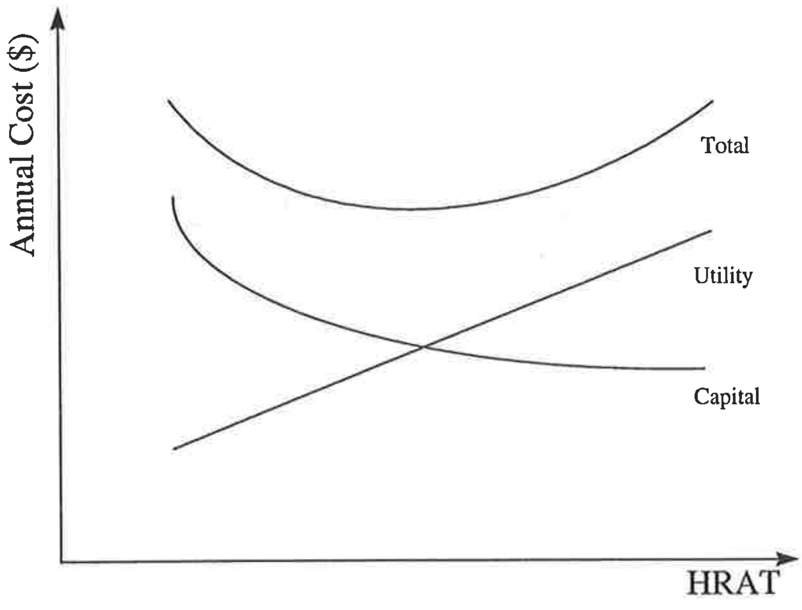


Figure 2.4: Total annual cost vs HRAT

2.4 Synthesis Phase

Let us now consider the key elements of each method.

2.4.1 Evolutionary Methods

In evolutionary methods, the final design is achieved by gradually evolving the initial design. The best known method in this category is the Pinch Design Method proposed by Linnhoff and coworkers. Four steps are normally undertaken when the design is performed.

- Supertarget
- Decomposition of the network
- Design of each sub-system
- Evolution of the initial design to final design.

Sophisticated methods have been developed for problem analysis (first two procedures). However, methods for the design stages (last two procedures) are less clear. Hence, the Pinch Design Method is believed to emphasise the targeting rather than the design (Linnhoff, 1993).

2.4.1.1 Review

Clearly, the global objective for network synthesis is to minimize total annual cost. However, in the early stages, the objective of the design may concentrate on a simpler objective, such as determining minimum total area or maximum energy recovery.

In the early stages of heat exchanger network synthesis development, energy was relatively inexpensive and so reducing capital investment or minimizing total area was the prime objective (Nishida, 1971, 1977, Ponton and Donaldson, 1974). This situation changed following a sharp increment of energy prices in the 70s and beginning of 80s. In response to the increase in the cost of energy, the objective shifted to maximum energy recovery (MER).

2.4.1.2 MER Design

Maximum energy recovery design plays an important role in evolutionary methods and is normally used to construct the initial design for a cost optimal design.

Linnhoff and Flower (1978a) proposed the first systematic approach, called Temperature Interval Method (TI), to achieve the MER design. In their method, the system was divided into several temperature intervals and hot and cold streams were matched within the interval. Linnhoff and Flower, (1978b) later proposed an evolutionary development method to reduce the number of units. Naka and Takmatsu (1982) proposed a method, which divided the system at the kinks of the composite curves into enthalpy interval rather than temperature intervals.

The work of Huang and Elshout (1976), Umeda et al. (1978, 1979, a, b), Linnhoff et al. (1979) in maximum energy recovery led to the development of a rigorous utility target and the discovery of the heat recovery pinch as a bottleneck for energy savings. The fundamental understanding of the heat recovery pinch and the effect of decomposition on energy recovery was presented by Linnhoff et al. (1979). Further work by Linnhoff and coworkers led to the presentation of Pinch Design Method (Linnhoff and Turner, 1981, Linnhoff and Hindmarsh, 1983). This MER version of the Pinch Design Method was later extended to a cost optimal version of the Pinch Design Method (Linnhoff and Ahmad, 1990).

2.4.1.3 Pinch Design Method

As mentioned earlier, the Pinch Design Method was originally developed for a MER design. First, minimum utility requirements were determined for a specified minimum temperature approach. Then the network was divided into two sub-systems (above and below the pinch). To produce a minimum utility design, the PDM ensures that no energy is transferred across the pinch, cold utilities are not used above the pinch and hot utilities are not used below the pinch. Heuristic rules, detailed by Linnhoff and Hindmarsh (1983), guide match selection during the design procedure.

The design for sub-system starts from the pinch on both sides and following CP matching rules are used to guide the match selection:

$CP_h \leq CP_c$ for above-pinch matches

$CP_h \geq CP_c$ for below-pinch matches

To reduce the number of the units, the load for a match is chosen to be as large as possible. This is referred as the "tick-off rule".

The two separately designed sub-systems are merged to provide an initial design. This initial design usually has too many units. Loop breaking is required to reduce the number of the units at final stage.

2.4.1.4 Cost Optimal Design

Based on the MER version of Pinch Design Method, Linnhoff and Vredeveld (1984) proposed a new heuristic tool called the Driving Force Plot (DFP) to guide the design to achieve a cost optimal design. The DFP guides the match selection so that energy consumption and total area are considered simultaneously. Another tool "The Remaining Problem Analysis" (RPA) was later presented to guide match selection between a cost optimal design by Ahmad (1985).

A comprehensive cost optimal version of the Pinch Design Method was presented by Linnhoff and Ahmad in 1990. It incorporated three heuristic rules CP-rules, the driving force plot (DFP) and the remaining problem analysis (RPA) into the design method as guidelines to help to reduce the total area.

Match selection is initially guided by the CP-rule together with the tick-off rule. The DFP and RPA are then employed to check if the match selected is appropriate for a cost optimal design.

The DFP shows the vertical temperature difference between the hot composite curve and cold composite curve against the cold composite curve. The matches may be chosen so that their temperature approaches follow the DFP as closely as possible.

RPA may be used in the synthesis to predict the penalty incurred with regard to the area or shell targets. At any stage, the problem is divided into two parts, the selected match and a remaining problem corresponding to this match. Like the DFP, this tool provides an indicator to allow the designer to distinguish between a poor and a good match for the cost optimal design. For an ideal match, no penalty is incurred.

Rule application is sequential - if the area target is not sufficiently approached by one rule, the next one is applied, and so on.

All rules for match selection in cost optimal design are heuristic. Consequently they do not provide sufficient conditions to select suitable matches for the cost optimal design. Trial and exhaustive search for match selection is normally required. The difficulty for match selection is obvious especially if the problem is large. These will impact on the design quality and a reasonable design may not be achieved.

In an attempt to improve the total cost of a network, "loop-breaking", "paths" and stream splitting are performed for evolution and continuous optimizations.

The other limitations of the pinch design method are its strict single ΔT_{min} and pinch decomposition. These limit the flexibility of the method, normally resulting in more units in the design.

The Dual Temperature Approach (DTA), firstly proposed by Colbert (1982), has been used to overcome the limitation caused by single minimal temperature approaches. The Dual Temperature Approach method defines two minimum temperature differences: the Heat Recovery Approach Temperature (HRAT) and the Exchanger Minimum Approach Temperature (EMAT). The DTA method achieves the same utility consumption as PDM but requires fewer shells and units. It simplifies the network and the designer has more flexibility.

To avoid the strict pinch decomposition, Wood et al (1985) allowed exchangers to cross the pinch, using stream splitting and by-passing. They discovered that it is possible to obtain a U_{min} design while achieving MER. Jones and Rippin (1985) and Jezowski (1990) found that two exchangers on both sides of the pinch may be merged into one. Although the structure of network is simplified without incurring an energy penalty, such matches may cause a severe area penalty resulting from the narrow temperature difference profiles in the exchangers (Jezowski, 1990).

Trivedi et al. (1989) proposed a method called Pseudo Pinch Design Method (PPDM). It combines the features of the dual approach temperature concept from Colbert (1982) and Pinch Design Method. The problem is divided into two independent networks at the pseudo pinch. The design strategy is similar to the PDM but it retains the flexibility of dual temperature concept. Designs from this method usually requires less evolution. Since α_n is allocated by heuristic, design quality is strongly influenced by the designer.

Suaysompol and Wood (199la & b) introduced a method, called Flexible Pinch Design Method (FPDM), to attempt to avoid the requirement for a variety of heuristic for the allocation of α_n. The Flexible Pinch Design Method is a refinement of the PPDM. To give larger driving forces for exchangers, the FPDM starts a design at HRAT and permits energy flow across the pinch in both directions. Extra utilities are not required due to the energy balance criss-crossing the pinch. FPDM uses simple and effective heuristic rules, such as stream splitting, subset equality and mirror image matches to design a simple network. Networks produced by the FPDM are usually simpler than that obtained by the PDM. However, since the FPDM mainly focuses on network simplification, the design from this method may require more capital investment.

2.4.1.5 The Problem with Different Film Transfer Coefficients

Most evolutionary methods, such as Pinch Design Method, concentrate on problems with equal heat transfer coefficients. They normally have difficulty handling problems with significantly different film transfer coefficients.

Nishimura (1975, 1980) presented a method to handle such problems. He used the following equation to guide match selection for a minimum area design. His method only considers problems in which a single hot or cold stream sequentially matches with cold or hot streams.

$$(T_1 - t)\sqrt{U_1} = (T_2 - t)\sqrt{U_2} = \cdots = (T_n - t)\sqrt{U_n} \qquad (2.5)$$

where t: temperature of single stream of one type (hot or cold)

T_j: temperature of stream j of the other type (cold or hot)

U_j: overall heat transfer coefficient between T_j and t.

Townsend (1989) extended Nishimura's method to the general case, which has multiple hot streams and multiple cold streams, by using stream individual "ΔT- contributions". This equation should apply to every stream temperature in the heat exchanger.

$$\left(T_i - t\right)\sqrt{U_i} = \alpha \qquad (2.6)$$

where ΔT_i: ΔT contribution by stream i

h_i: film coefficients of the streams

Ahmad et al. (1990) stated that α is not correctly defined unless the ΔT- contributions maintain the interval enthalpy balance. This can be done by solving the following linear equations for ΔT - contributions. Different stream ΔT - contributions cause streams to have different temperatures at an enthalpy interval edge.

$$(T_j - t)\sqrt{U_j} = \alpha \qquad j = 1,\cdots,S_i \qquad (2.7)$$

$$\sum_{j=1}^{S_i} CP_j(\Delta T_j - \Delta T_k) = 0 \qquad (2.8)$$

Rev and Fonyo (1991, 1993) presented a method referred as the "Diverse Pinch Concept" to handle the problem with transfer coefficients that differ significantly. The ΔT - contribution for stream i was defined by the following equation. A stream is vertically shifted by adding or subtracting a ΔT - contribution. Cascading is performed to determine κ. The diverse pinch approach results in the unambiguous treatment of the diversity problem.

$$\Delta T_i = \kappa h_i^{-z} \qquad z \in [0.5, 1.0] \qquad (2.9)$$

2.4.2 Mathematical Techniques for HEN Synthesis

In mathematical programming methods, HEN problem is described as a mathematical problem and the established mathematical model is solved by mathematical programming solvers, such as LP, NLP, MILP or MINLP. Which solver is applied depend on the feature of the mathematical models.

To postulate the mathematical optimisation model for a heat exchanger network, the network topology is required. Unfortunately, the topology is not available before establishing the model and must be solved for as part of the optimisation process. This means that heat exchanger network synthesis is considerably more difficult than general parameter optimisations.

Synthesis of a heat exchanger network can be converted into a normal parameter optimisation problem by fixing its potential topology or structure. Hence, a potential structure or match pattern is assumed for each method so that the mathematical models based on the structure or match pattern could be established. Since industrial HEN problems may be very complex, reasonable simplification for the topology and match pattern is necessary so that the resulting mathematical models are capable of being solved.

Two key issues arise for mathematical programming methods for this problem. The first is how to decompose the system into sub-systems. The second is the nature of the potential match pattern for each sub-system.

The mathematical programming methods can be grouped into global simultaneous optimisation methods and sequential optimisation methods according to how the trade-off is performed. For global optimisation methods, trade-off between utility cost and capital investment is taken into account simultaneously. This optimisation strategy is employed in the most recently developed methods. By contrast, for sequential optimisation methods, the design is sequentially optimised through a number of stages to the final design.

2.4.2.1 Sequential Optimisation Methods

Prior to 1980, several methods based on the LP model were proposed. However, the milestones of the research by the mathematical programming were two formulations known as "transportation model " and " transhipment model". These were proposed by Cerda and Westerberg (1983), and Papoulias and Grossmann (1983) respectively to achieve maximum energy recovery as well as minimum number of units.

In the transportation model, the commodity is directly transported from the sources to the destinations. In transhipment model, the commodity is transported from sources to intermediate location (warehouses), then to the destination. The transhipment model can be considered as a variation of the transportation problem and deal with the optimal allocation of resources.

Both methods sequentially solve the problem. First, a design with minimum utility consumption for a given ΔT_{min} is solved as a linear programming (LP) problem. Cerda and Westerberg employed the transportation model whilst Papoulias and Grossmann used a transhipment model. Then, the minimum number of units is found as a MILP problem (Papoulias and Grossmann, 1983). The solutions are in the form of the heat load distribution (HLD). The system is divided into sub-systems at pinch points, each subsystem is treated separately and no matches are allowed to cross the pinch.

Figure 2.5 illustrates the energy flow pattern for each temperature interval for the transshipment model. In the heat exchanger network, energy is regarded as a commodity. Hot streams and hot utilities are treated as sources, and cold streams and cold utilities are considered as destinations. Energy is transported from hot streams to the corresponding temperature intervals (intermediate place), and then to the cold streams. Energy may flow from a particular interval to the next lower temperature intervals. This energy is the residual that cannot be consumed in the current interval. Consequently, it must flow to a lower temperature interval.

Jones and Rippin (1985) simplified the transhipment and transportation model and solved the problem without partitioning at the pinch. Their work demonstrates that an excessive set of HLDs (Heat Load Distribution) exist for a synthesis task. For example, at least 3000 HLDs are possible for a system with 10 streams.

As these methods solve the problem sequentially, the trade-off may not be accounted for accurately.

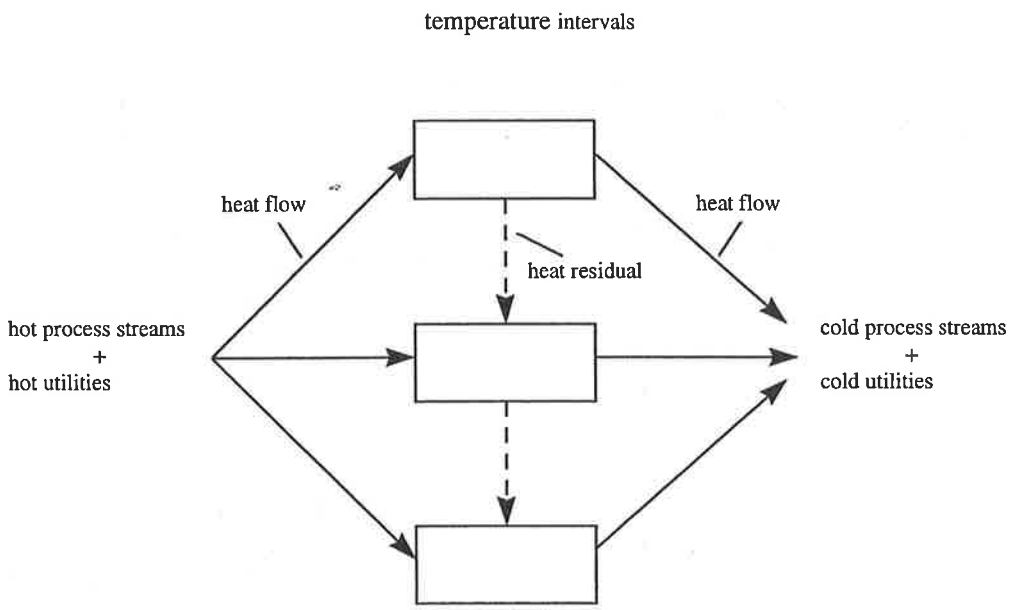


Figure 2.5: Transhipment model

2.4.2.2 The Global Optimisation Methods

To overcome the problems of the sequential optimisation methods, Floudas et al, (1986) proposed a global optimisation method, which optimises the utility cost and capital investment simultaneously. The method is based on a structure and matching pattern called a "Superstructure".

The superstructure embeds all potential matches for the HLD and makes the generation and optimisation of the network possible by non-linear programming (NLP).

Floudas and Ciric (1989) developed an improved method based on a generalized match-network hyperstructure which contains all possible network configurations and all possible process stream matches (see Figure 2.6). The hyperstructure is constructed from superstructure associated with each process stream. There are two components in the model. The first phase involves solution of the transshipment model for selecting stream matches and heat loads. The second phase employs the hypersturcture model to determine the structure of the network and actual area of the heat exchanger. The transshipment and hyperstructure models are incorporated into a single model so that match selection and area can be optimised simultaneously by using a MINLP. The two separate steps, a MILP step which determines HLD and a NLP which optimises area, have been combined into a single stage. Both the utility target and the heat recovery approach temperature are constant in the model. The system is still partitioned at the pinch point and a General Benders decomposition strategy was used to solve this complex MINLP problem.

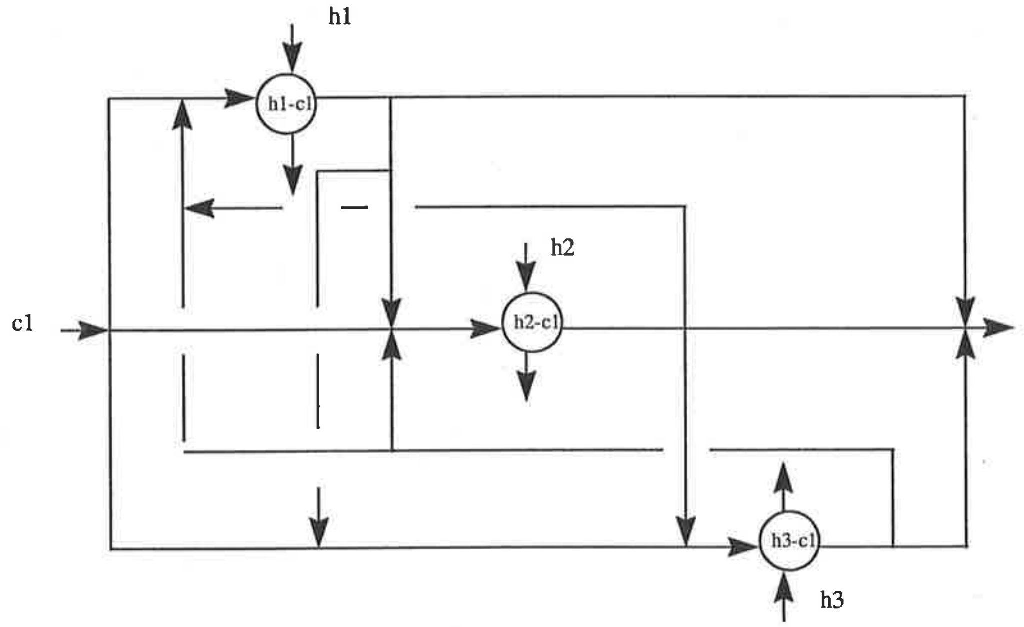


Figure 2.6: Hyperstructure

Gundersen and Grossmann (1990) refined Floudas' method (1986) by introducing a penalty term into the objective function to avoid driving forces falling below the

EMAT. The EMAT value is used as a lower bound rather than as an optimisation variable. Their model consists of a vertical MILP transhipment model.

Yee and Grossmann (1990) proposed a MINLP mathematical model. Both energy and capital cost are incorporated in the model and they are optimised simultaneously. The proposed representation of the problem is by a "stage-wise" superstructure. This superstructure is an extension of the work of Grossmann and Sargent (1978).

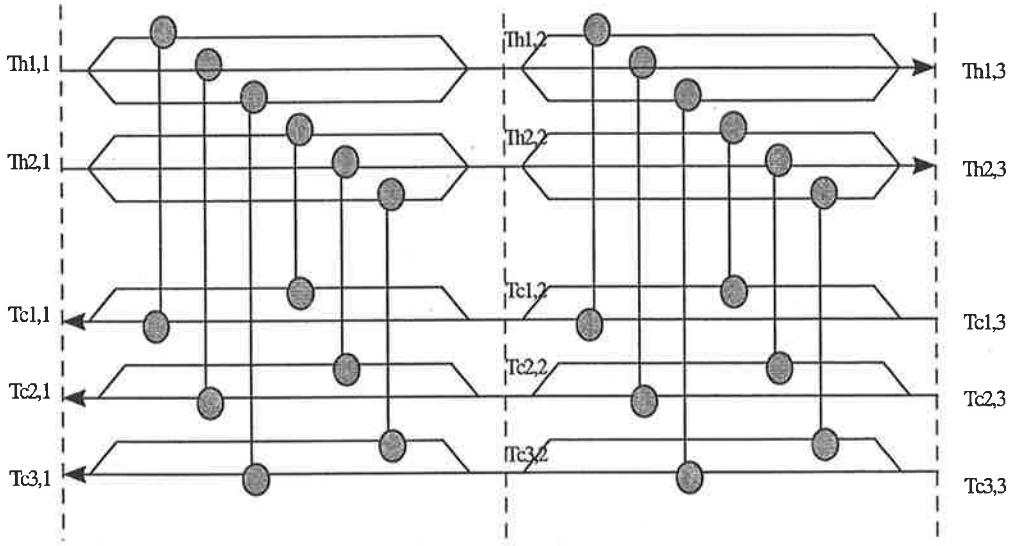


Figure 2.7: The Superstructure for two stage

In their superstructure, a potential match could occur to any two different kinds of streams within a stage (Figure 2.7). Within each stage, the superstructure is of the form of the "spaghetti" design. Stages are used to take place the temperature intervals and the boundary temperatures of stages are treated as variables. The number of stages is a parameter which must be decided by user. It is normally smaller than the number of temperature intervals. In practice, the number of the stages is increased until a reasonable result is achieved. The authors recommended choosing the value as the maximum value of the number of the cold streams and hot streams. A superstructure with two stages is illustrated in Figure 2.7. Compared to the hyperstructure, this representation significantly simplifies the structure within two adjacent boundary temperatures by only considering the "splitting" case.

This global MINLP problem is solved by a combined Penalty Function and Outer-Approximation Method (Viswanathan and Grossmann, 1990). The simplified model features a non-linear objective function with linear constraints. Pinch decomposition is not required.

However, due to the solution techniques of current MINLP solvers, implementation of a MINLP causes severe computational difficulty for large-scale problem. Even a simple network problem may result in a large-scale combinatorial problem that can not be tackled satisfactorily by MINLP.

To overcome this problem, Dolan et al (1989, 1990) and Athier et al. (1998) applied the simulated annealing algorithm which is insensitive to the starting point to solve the HEN problem. The principal disadvantage of the simulated annealing algorithm is that a very large number of trials are required. this may impose a severe computing penalty.

Zhu et. al. (1995) proposed a method to help find a good initial structure or topology for the optimisation problem. With the initial design, the HEN problem is transferred to a normal parameter optimisation problem which maybe a NLP or MINLP problem. To find an initial design, the system is decomposed by blocks which include one or more enthalpy intervals defined by 'kink points'. In each block, a quasi-composite line is used to approximate the true composite curve. For each possible match, the actual area required $A_{ij,actual}$ and the quasi-composite based "ideal area" $A_{ij,quasi\ ideal}$ for the match are calculated. Then a match combination is selected and evaluated by several heuristic rules. Normally several alternatives are required.

2.5 Discussion and Conclusions

Although significant contributions have been made to the energy-integration problem, problems still exist for both mathematical programming methods and evolutionary methods.

Mathematical programming methods are limited by the available solvers, such as GAMS. Sometimes it is very difficult to converge the problem to a global solution, particularly for industrial-sized problems. This severely limits the application of mathematical programming methods.

Evolutionary methods such as the Pinch Design Method have been successfully applied to industrial sized heat exchanger network synthesis. However, the methods available are more like an analysis rather than a design method. Several problems or questions should be addressed:

- Heuristic rules, which guide the match selection, are often not sufficient to achieve the desired objective and many alternatives may need to be evaluated. In general, existing heuristic rules for match selection are time consuming, inefficient and sometimes difficult to implement.

- A simple but efficient design procedure is required for parts of stream away from the pinch or partition point.

- When stream film heat transfer coefficients differ significantly, the existing decomposition strategies, such as "pinch decomposition" and "block" encounter difficulties in discovering reasonable design.

- The key trade-off between capital and energy costs may not be easily addressed. This limited the efficiency of the methods for large-scale problems.

- A systematic but easily implemented design method is required for problems with constraints, such as forbidden matches and imposed matches.

In this research, a binary tree decomposition strategy is proposed. Design for a problem starts from root node without decomposition. An index called dominant cost component of the total annual cost will be proposed and used to decide if further decomposition for the node is required. If decomposition for the root node is necessary, the root node will be decomposed into two child nodes. Each child note will be then treated as a root node again until decomposition of any leaf nodes are no longer required. Finally, the child nodes are combined to form the design for their parent nodes. This decomposition strategy will also overcome the difficulty in the design when the heat transfer coefficients differ significantly.

On the detail design stage, a new straightforward match selection procedure is proposed. For each problem, an initial design is determined for the problem using a match selection model. The remaining parts of the problem which do not participate in the process matches, are treated as a new problem. This procedure is repeatedly applied until no feasible matches are available.

Despite the fact that the design for a node gradually evolves to the final design, match selection is determined quantitatively by a match selection model rather than by heuristic rules. This alleviates uncertainty, excessive time consumption and any inefficiency caused by heuristics rules. The effort for a design is significantly reduced and the final design depends primarily on the method than the designer's bias.

Match selection procedures for the remaining parts provide the designer with a systematic procedure for the part of streams away from the pinch or partition point.

Finally, to overcome any inaccuracies in the trade-off between utility and capital cost in evolutionary method, an optimisation of the partition temperatures is undertaken for the final fixed topology. The trade-off does not involve complex programming. For example, optimisations can be undertaken using EXCEL for a moderately sized problem.

The new method is insensitive to the size of the problem, hence, it can solve industrial size problems. It can easily handle variant situations by simply changing the cost formula or value for the potential individual match, such as a forbidden match or preferred match. Therefore, consideration for safety and layout can be easily incorporated into the design ensuring that the final design is more acceptable. The design method can easily be extended to handle more detailed costing. For example, if piping cost and the layout of the units are known, then piping cost and pumping cost may be incorporated into the cost formula for individual matches.

CHAPTER 3

A NEW DECOMPOSITION STRATEGY: BINARY TREE DECOMPOSITION

3.1 Introduction

One of the key issues in heat exchanger network synthesis is the decomposition strategy for the system. It usually has a significant impact on the topology and the final design of heat exchanger network.

When the heat exchanger network synthesis is performed, the system is normally decomposed into two or more sub-systems. For example, in evolutionary methods, such as the Pinch Design Method, the system is divided by pinch decomposition (Linnhoff et al., 1982, 1990). The divided systems above and below the pinch are designed separately and no cross pinch matches are permitted.

However, pinch decomposition may not work for problems with substantially different heat transfer coefficients. Streams may need to be redistributed between the sub-systems (Gundersen et al.,1990 and Zhu et al.,1995).

In mathematical programming methods, the system may be divided into more than two sub-systems. The decomposition strategy will impact on the complexity of the final design. Saboo et al. (1986) developed an LP formulation based on the temperature interval (TI's) defined by 'kinks' in the composite curves. The number of TI's is increased until the criteria is satisfied or the problem dimensionality become excessive. Colberg and Morari (1990) proposed a NLP method to calculate the area and capital cost targets. Their NLP models are based on the temperature interval (TI's) from the composite curves. However, the number of TI's approximately equals twice the total number of streams.

To reduce the number of intervals or sub-systems, Yee and Grossmann (1990) proposed a stage-wise superstructure. They recommended that the number of the stages equal the maximum number of hot streams and cold streams. However, sometimes the number of stages must be increased to design a network with minimum energy consumption (Daichendit and Grossmann 1994).

Zhu et. al. (1995) proposed the block concept to divide the system into blocks. The number of the blocks was based on the composite curves and each block spanned several composite segment or temperature intervals. The block method may reduce the number of sub-systems.

In this chapter, a novel strategy of decomposition, called binary-tree decomposition, is presented. With this new decomposition strategy, problems with substantially different film transfer coefficients and problems with equal film transfer coefficients can be solved using an identical match selection and design procedure. No special treatment is required.

Binary-tree decomposition provides an insight into the system's dominant cost component rather than simply decomposing the system by temperature intervals or the number of streams. The number of the nodes in the binary-tree decomposition depends not only on the stream data but also on the cost laws and utility prices. Subdivision of a node to spawn child nodes will be determined by the dominant component of the total annual cost for the design of the node, which may be either capital or utility cost.

3.2 Decomposition and Design

Decomposition may influence the final design in many ways. An obvious simple consequence is the number of the units in the design. Decomposition strategy determines the distribution of hot streams and cold streams between the different sub-systems, hence, it will strongly influence the streams participants in the individual matches.

For the evolutionary methods, such as the Pinch Design Method, decomposition plays an even more important role. It determines key indicators such as the maximum energy recovery and hence, it has a critical role in achieving a good- quality design.

3.2.1 Pinch Decomposition and Design

The discovery of the "pinch" as the bottleneck of the energy recovery for a system lead to the proposal of the Pinch Decomposition and the Pinch Design Method.

The initial stage of the Pinch Design Method always decomposes the problem into two sub-systems (above pinch and below pinch). These sub-systems are designed separately. Ideally, each sub-system only requires either cold utility or hot utility. Matches are not permitted to cross the pinch point as an energy penalty is incurred.

Pinch decomposition is strongly influenced by the value of HRAT (ΔT_{min}). Different minimum approach temperatures produce different decompositions. The resulting sub-system may contain different hot and cold streams. Such differences lead to different initial designs and consequently different final designs.

Previous workers have noted the difficulty of evolving a network to the optimal design given particular sub-systems (Linnhoff and Ahmad 1986,1990). Design commenced from a poor estimate of ΔT_{min} (or HRAT) may be impossible to evolve to the optimal design (a 'topology trap' - Linnhoff and Ahmad, 1986 a & b).

To discover the cost optimal design, pinch methodology normally evolved several designs from different HRATs (Linnhoff et. al, 1982). The minimal cost design is retained. This strategy is inefficient and significantly increases the design task and the time required. The 'Supertargeting' algorithm was proposed to discover the optimal ΔT_{min} prior to detailed design. The algorithm's estimate of capital cost is only rigorous for problems with equal heat transfer coefficients. But the optimal HRAT is normally acceptable given the flat nature of the response surface.

3.2.2 Problem with Substantially Different Film Heat Transfer Coefficients

A second difficulty encountered when evolving the MER design to a cost optimal design may be caused by streams with widely different film transfer coefficients. In such cases, strict vertical heat transfer does not ensure low area and investment cost. Deliberate cross pinch matches may be required to reduce capital cost (Gundersen and Grossmann, 1990, Zhu et. al. 1995). To overcome this problem, Gundersen and Grossmann (1990) introduced the stream individual contributions to the global minimal temperature approach. Unfortunately, the optimal design was not directly determined by their criteria.

Zhu et. al. (1995) proposed a set of procedures to discover the optimal design for the problems with widely different heat transfer coefficients. First, the diverse pinch approach generated the modified composite curves and streams moved their location. For example, in Figure 3.1, cold stream c1 and c3 are shifted across the pinch to a different "above pinch" system. These modified sub-systems form the base for an optimal design using MINLP.

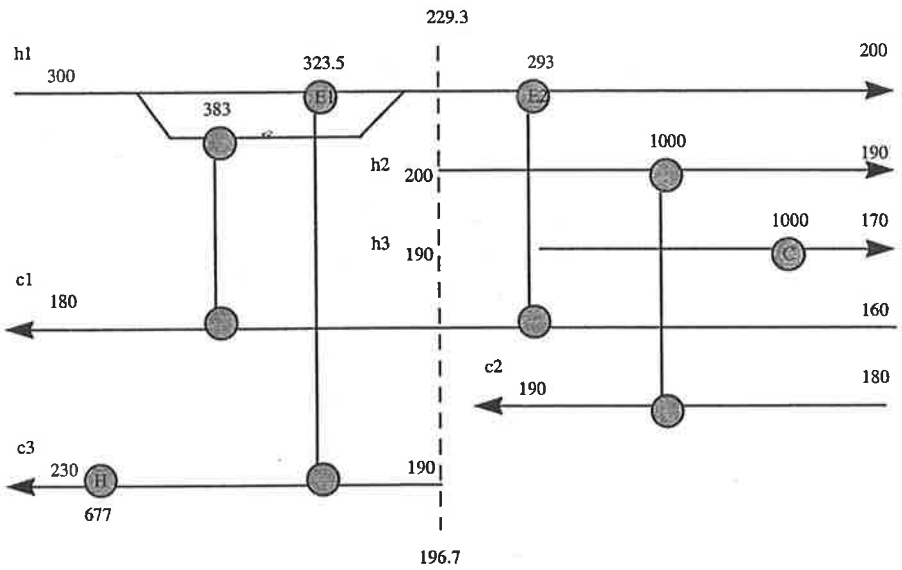


Figure 3.1: The initial design from Zhu et. al. (1995)

It is clear that Gundersen and Grossmann, and Zhu et al. achieved the optimal design by applying a non-standard method to redistribute the streams into different sub-systems. The normal design procedure failed as a consequence of the decomposition method. To overcome this deficiency of conventional methods, a new decomposition strategy is proposed.

3.3 New Decomposition Strategy

Traditionally, a system decomposition is solely decided by stream parameters and their thermodynamic properties. Cost considerations do not have an impact on system decomposition. However, the cost trade-off strongly influences the final design. Hence, it is logical to account for their influence in initial stage of the design - namely, during system decomposition.

To aid with this process, a new variable "d" (the dominant component of the total annual cost) is defined. Based on the value of this dominant component, a new decomposition strategy will be proposed.

3.3.1 The Dominant Component of the Total Annual Cost

The total annual cost of a network may be simply split into two components, namely energy cost and annualized capital cost. Clearly, different cost laws will alter the relative contributions of capital to total cost and thus affect the network design. This idea clearly influenced the development phases of heat exchanger network synthesis.

In the early phase of the problem solution, energy prices were relatively low, consequently capital investment dominated the cost. The key issue of synthesis focused on reduction of total area of heat exchangers to reduce capital investment. This situation was altered following the "oil crisis". Steeply increased oil price dramatically increased the relative contribution of utility cost to the total annual cost. The key issue for network designing changed from reducing capital investment to saving energy. This led to the development of the Maximum Energy Recovery (MER) concept which is fundamental to Pinch Design Methods.

After 1986, the oil crisis eased and utilities became cheaper. Business priorities were no longer solely focused on energy efficiency. Consequently, the objectives of heat exchanger network synthesis became more sophisticated. Minimal total annual cost replaced the maximum energy recovery or minimum total area as the final objective of network synthesis.

Energy reduction and saving of capital investment can not be achieved simultaneously, so optimal total annual cost design has to be achieved by a classical trade off between energy and capital. Clearly, the maximum energy recovery design is a special case of the optimal total annual cost design for case where capital investment is relatively small. By converse, minimum total area designs are clearly favoured when utilities are relatively inexpensive.

Despite this increased sophistication in analysis, the design methodologies remain relatively unaltered. For example, in evolutionary methods, a MER design is still exploited to construct the design backbone. The trade off is addressed by evolution of this simple initial network.

The Pinch Design Method works well for most cases in which energy cost are dominant. However, the method experiences difficulty in finding an optimal design for capital cost dominant problems. This has been demonstrated by Gundersen and Grossmann, (1990) and Zhu et. al. (1995). In such situations, pinch decomposition produces very complicated MER designs or else results in design which can not be evolved to the cost optimal design.

In this work, a simpler (more general) decomposition method for cost optimal design is proposed. The system will be categorized into utility cost dominant and capital cost dominant problems rather than problem with equal heat transfer coefficients and problem with widely different heat transfer coefficients. The decomposition strategy to be followed depends on the dominant component of the total annual cost.

3.3.2 Analysis of the Dominant Component

The fractional contribution of utility cost to the total annual cost (d) is readily defined as:

$$d = \frac{Cost\_of\_utilities}{Total\_annual\_cost}$$

The value of d for a network indicates whether energy or capital dominates the total annual cost. The key problem is " what d value determines if the problem is energy cost dominant or capital cost dominant problem". The answer to this is clearly fuzzy but a broad crisp guideline may be set.

Based on experience derived from a variety of test examples, d = 0.5 is suggested as the critical value. If d exceeds 0.5, utility cost is the dominant contributor. Otherwise, capital cost is said to be the dominant contributor to the total annual cost. Clearly, there is a region of some uncertainty about this value but the nature of the response surface means that this is not a serious problem.

3.3.3 Capital Cost Dominant

When the dominant component is capital cost, any reduction in capital investment will substantially reduce the overall cost. This scenario is likely when the cost of utility is relatively cheap or the utility requirement is low. The obvious way to reduce capital cost is by reducing the number of units and by improving the allocation of driving forces to individual exchangers.

Decomposition of the system into sub-problems normally increases the total number of both hot and cold streams thus producing a design with more units. Clearly, a design without decomposition will produce a system with fewer units. However, such designs normally include matches that cross the pinch thereby increasing the energy consumption. This energy penalty is compensated for by the more significant reduction of capital cost. The total annual cost for the design is likely to be smaller. Hence, when capital cost is dominant, the system will be treated as a simple entity without decomposition.

3.3.4 Energy Cost Dominant

Conversely, if utility cost is dominant, any reduction in energy consumption will likely produce a more significant decrease of the total annual cost compared to reductions in capital cost. Hence, energy saving becomes the prime issue for an energy dominated problem. The decomposition for a MER (or near MER) design will be attractive and a decomposition is required. Should a pinch exists, then the decomposition will be a pinch decomposition. The rules for MER design are followed and no cross pinch matches are permitted.

3.3.5 Binary Tree Decomposition

Such a decomposition strategy is appropriately represented by a tree structure. The design commences from a root node, where the system is treated as a single entity. The root node may be decomposed into two child nodes. These child nodes may be further decomposed. The dominant component of the total annual cost for the design determines to what level the decomposition proceeds.

If root node is a capital-cost dominant problem, no child nodes are required and only a single node exists in the binary tree (Figure 3.2). If the root node is confirmed to be an energy-dominant problem, then this root node is decomposed into two child nodes. The binary tree has two leaf nodes (Figure 3.3). Whether "grandchild" nodes are required depends on the d values of each child node or if the designs for each child nodes become ideal. In an ideal design situation, only a single type of utility is required for each node, sub-systems above the partition point only require hot utility whereas sub-systems below the partition point only require cold utility. Further decomposition cannot provide any energy saving, hence, it is not encouraged.

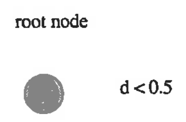


Figure 3.2: The root node (capital-dominant problem stop here)

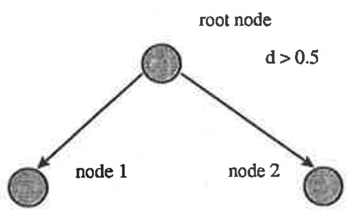


Figure 3.3: A binary tree with two leaves

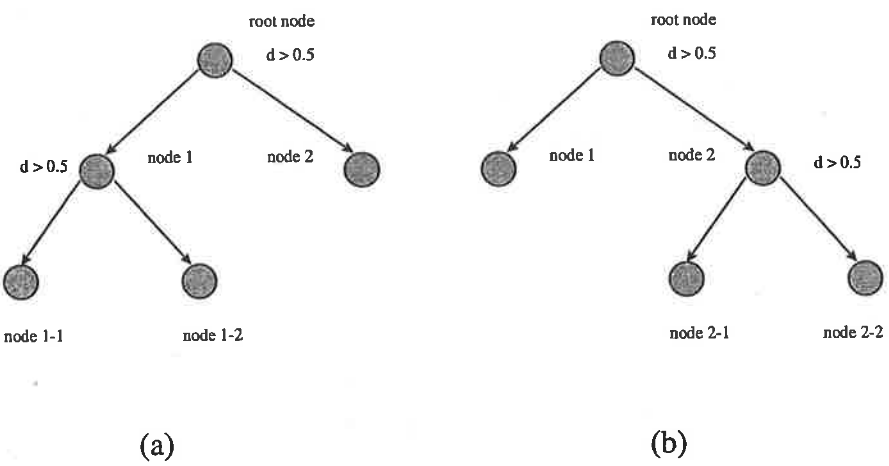


Figure 3.4: Binary tree with three leaves

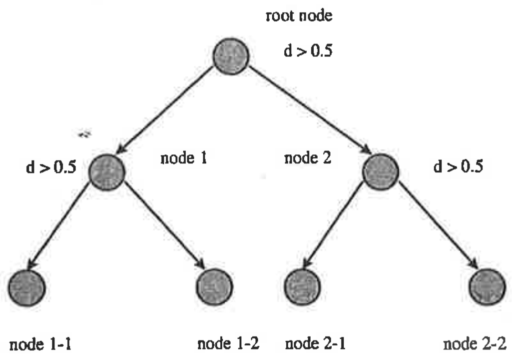


Figure 3.5: Binary tree with four leaves

Figure 3.4 (a) shows a binary tree with three leaves. Node 2 and node 1-1 and node 1-2 are either capital dominant or in ideal situation. In Figure 3.4 (b) Node 2 and node 1-1 and node 1-2 are either capital dominant or in the "ideal" situation. A binary tree with four leaves is shows in Figure 3.5. In this decomposition, node 1-1, node 1-2, node 2-1 and node 2-2 are all either capital dominant or in ideal situation.

In some instances, leaf node may require only hot utility or cold utility, but the driving forces for some units may be particularly close to the EMAT value. In such cases, decomposition of the node may result in improved driving forces and save capital cost. Further decomposition may be undertaken until improvement is insignificant.

3.4 Examples of Binary Tree Decomposition

Two case studies illustrate how such decomposition is performed and its impacts on the final design. Detailed design and analysis for both cases can be found in Chapter 5.

3.4.1 Case One

Considering the following problem studied by Gundersen et al. (1990) and Zhu et al. (1995). The relevant stream data are shown in Table 3.1. The feature of the problem is that the heat transfer coefficients differ by an order of magnitude. The optimal design for this problem can not be found by normal design procedures.

The superstructure algorithm suggests that ΔT_{min} = 20 K (HRAT). Figure 3.6 illustrates the design from the Pinch Design Method with this global ΔT value (Gundersen et al., 1990). The design requires a total area of 674 m^2 and annualised capital investment $256,750. Utility consumption is 1000 kW for hot utility and 1000 kW for cold utility.

The design with criss-pinch matches is shown in Figure 3.7. Total area decreases from 674 to 494 m^2 and the total annul capital investment falls from $256,750 to $211,120. Utility consumption remains unchanged. The design in Figure 3.6 can not be evolved to this design (Gundersen et al., 1990).

Table 3.1: Stream data for case study 1

stream	h1	h2	h3	steam	c1	c2	c3	water
Tin(°C)	300	200	190	350	160	180	190	30
Tout(°C)	200	190	170	350	180	190	230	50
Cp(kW/k)	10	100	50		50	100	25	
h(kW/m^2K)	0.1	1	1	4	0.1	1	1	2
Q(kW)	1000	1000	1000		1000	1000	1000	

exchanger cost($): $10000+1000A^{0.8}$

cost of hot utility: $ 110/kW yr.

cost of cold utility: $ 10/kW yr.

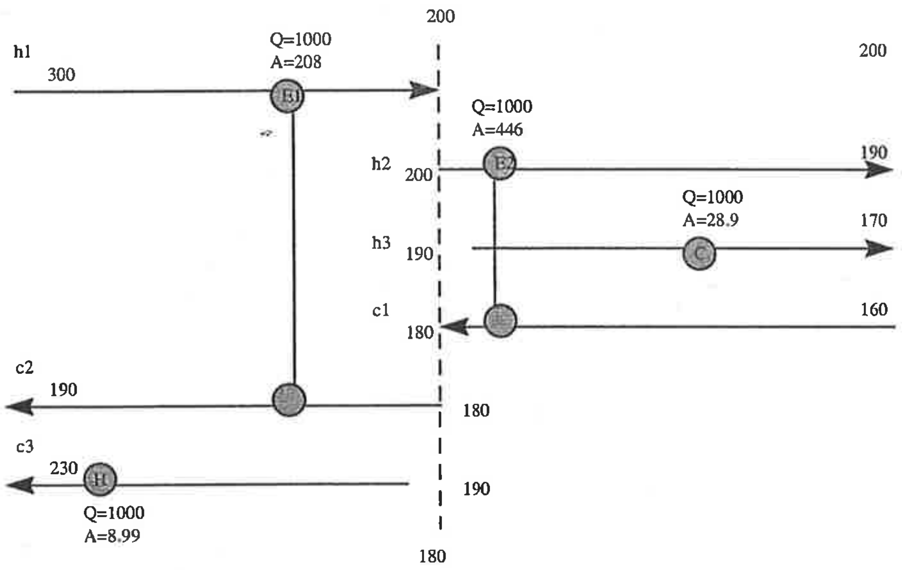


Figure 3.6: Pinch design for case study 1 at HRAT= 20 K
(Gundersen et al, 1990)

With the new decomposition strategy, the design commences from the root node and the system is treated as a single entity with no decomposition. It produces a design for the root node involving matches h1-c1, h2-c2 and h3-c3. Match h3-c3 does not recover any energy and h3 and c3 reach their target temperatures by using cold utility or hot utility. This design achieves a total annual cost of $339,210. Its energy cost is $120,000 - less than 40% of the total annual cost (d = 0.4). Hence the root node is a capital-cost dominant problem and further decomposition is unnecessary.

This design is identical to the optimal design shown in Figure 3.7. The optimal design is easily discovered using the new proposed decomposition strategy. The problem is a capital cost dominant problem and the binary tree has only single node – the root node.

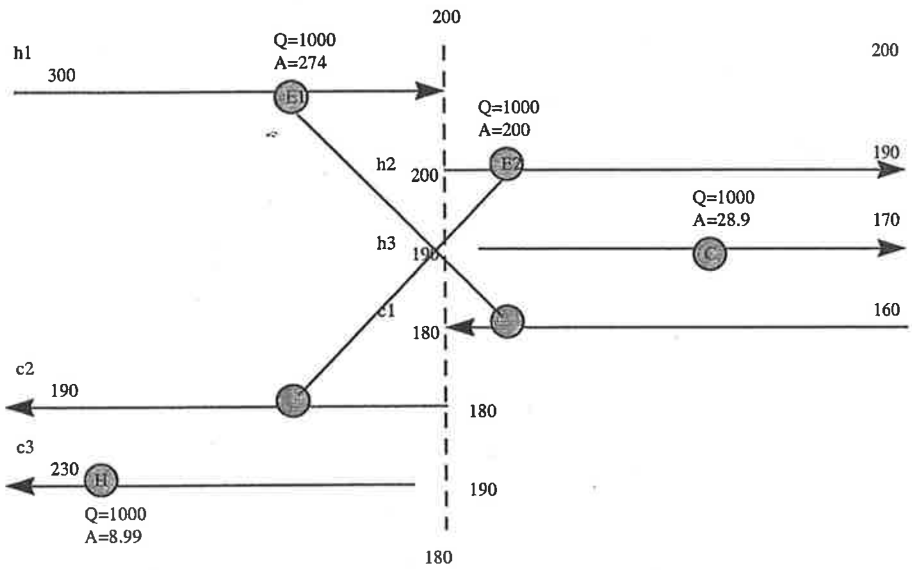


Figure 3.7: Criss-pinch design for case study 1 at HRAT= 20 K (Gundersen et. al., 1990)

3.4.2 Case Two

This simple example has been studied by Linnhoff et al.(1982), Yee and Grossmann (1990), Ciric and Floudas (1990) and Zhu et al. (1995). The stream data and relevant cost data are shown in Table 3.2.

Table 3.2: Stream and cost data

stream	h1	h2	steam	c1	c2	water
Tin(K)	443	423	450	293	353	293
Tout(K)	333	303	450	408	413	313
Cp(kW/K)	30	15		20	40	

U= 800(Wm^2/K) for all matches without involving hot utility (steam)

U=1200(Wm^2/K) for matches involving hot utility (steam).

Annual exchanger cost: ($) $1000A^{0.6}$ for exchanger, cooler.

Annual exchanger cost: ($) $1200A^{0.6}$ for heater

Hot utility cost: 80 $/kWyr

Cold utility cost: 20 $/kWyr

Level one design — the root node

The first level design is illustrated in Figure 3.8. The total annual cost is $106,640 with annual hot utility consumption and cold utility consumption equal to 500 kW and 900 kW respectively. The utility cost is $58,000, a contribution of 54 percent of the total annual cost. As $d \geq 0.5$, this case is an energy-cost dominant and further decomposition is required.

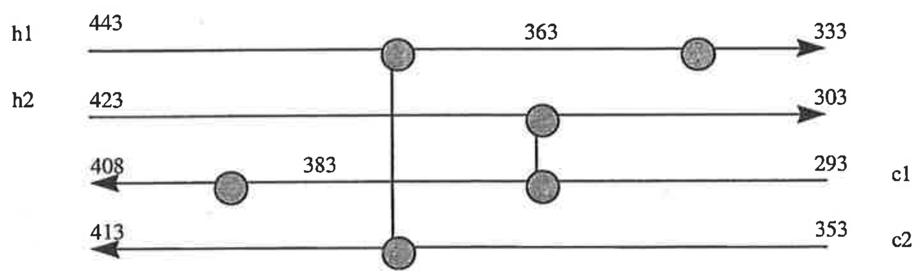


Figure 3.8: Design for root node, the total annual cost: $106,638

The level two node design

The system is decomposed into two child nodes above and below pinch using a HRAT = 5.6 K (superstructure).

The design for node 1 is presented as Figure 3.9. The total annual cost and utility cost are $44,800 and $160 respectively. Since the utility cost constitutes less than 1 percent of the total annual cost, the design is capital cost dominant and subsequent decomposition of this branch is not required.

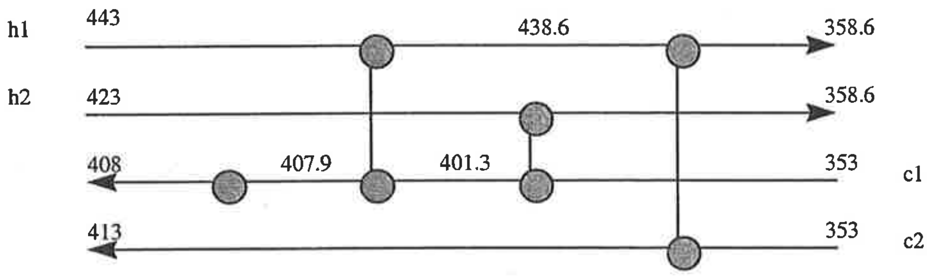


Figure 3.9: Design for node 1

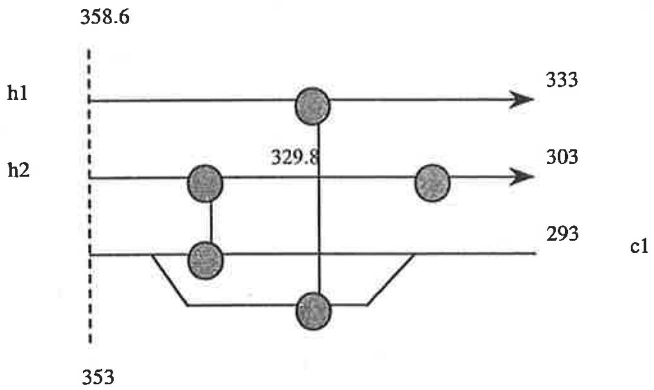


Figure 3.10: Design for node 2

However, node 2 is composed of a single cold stream and two hot streams. The design for node two is shown in Figure 3.10. The total annual and utility costs are $36,100 and $8,040 respectively. Since the utility cost contributes about 22 percent of the total annual cost (d = 0.22), the node is capital cost dominant problem and further decomposition is unnecessary.

The binary tree for this decomposition has two leaf (or child) nodes (1 and 2). Combination of the designs produces a design for the problem shown in Figure 3.11.

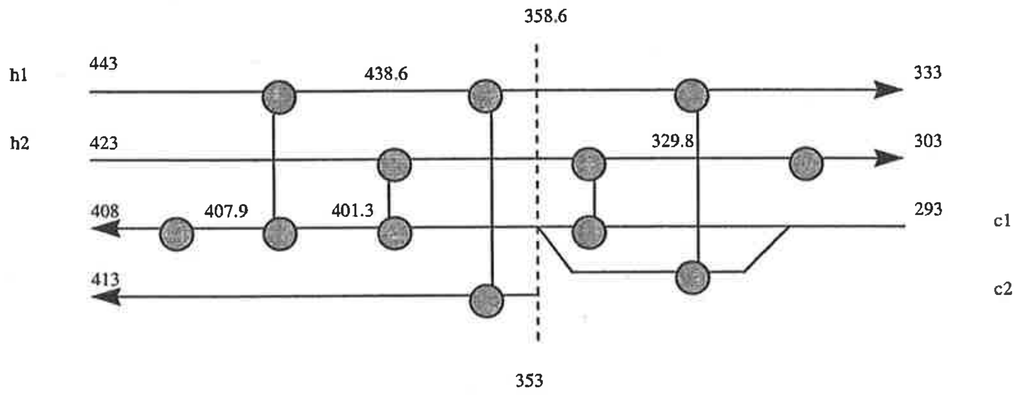


Figure 3.11: Combination of the two design for node 1 and node 2, the cost: $80,900

3.5 Conclusion

A new decomposition strategy is proposed in this chapter. It is best described as a tree decomposition. The method provides insight into the dominant component to the total annual cost. The level of expansion for any node is determined by the stream data as well as the cost laws and utility prices.

The problem need only be catalogued into two types either utility cost dominant or capital cost dominant. This categorization will determine if further decomposition is required or not. In other words, this simple criterion will determine the tree structure of the nodes.

Given this more generalized decomposition strategy, problems with widely different heat transfer coefficients and those with equal heat transfer coefficients are not treated differently. Both types of problems can be solved by using identical match selection and design procedures. Special treatment, such as diverse pinch, etc is not required.

CHAPTER 4

THE MATCH SELECTION MODEL

4.1 Introduction

The match selection method is a key phase to distinguish between the different synthesis methods. According to the methods for match selection, existing methods fall into two broad categories, evolutionary methods and mathematical programming methods.

In mathematical programming methods, the synthesis task is posed as an optimisation model. Matches are designated by binary variables. For a binary variable such as x_{12}, $x_{12} = 1$ implies a match between hot stream h1 and cold stream c2 and $x_{12} = 0$ means no match exists between the two streams. Matches in the design are selected by mathematical programming techniques, such as MILP or MINLP (Yee and Grossmann, 1990).

Mathematical programming methods are limited by the characteristics of the models and the available solvers. Convergence to a global solution sometimes is very difficult, particularly when the size of HEN problem exceeds 10 streams. By contrast, a typical industrial problem usually consists of 30-80 streams. This severely limits the application of mathematical programming methods in many instances.

By contrast, in evolutionary methods, (eg. the Pinch Design Method), matches are selected by heuristic rules. These heuristic rules are often insufficient to guarantee the desired objective, such as minimum total annual cost (Linnhoff and Ahmad, 1990).

Normally, many alternative designs are evaluated. An exhaustive search for match selection can be quite cumbersome particularly for large-scale problems.

Such uncertainty in the match selection procedure means that design quality can not be guaranteed. Normally, a good design is to some extent determined by the experience and expertise of the designer.

In this study, a new match pattern and topology called a simplified superstructure is proposed. As no interaction exists between individual matches in the simplified superstructure, the matches may be designed and optimised individually. Based on the match pattern, a match selection model is developed. The mathematical models can be solved by integer programming and the complexity caused by mathematical programming methods is avoided. Likewise, the uncertainty and exhaustive search characteristics of the evolutionary methods is also overcome by exploiting this match selection model.

Based on this match selection model, a match selection procedure for the HEN system is finally proposed. The new match selection procedure is simple and straightforward. First, an initial design is discovered by the match-selection model. Then, the remaining parts of the problem, which do not participate in the process-process matches and are often located away from the partition point or pinch, are treated as a new problem and solved by the same procedure. These procedures are repeated until no feasible matches are available.

4.2 A New Match Pattern

In heat exchanger network synthesis, both network topology and unit design parameters must be decided. This causes the heat exchanger network synthesis problem to differ from general parameter optimisations. However, the synthesis of heat exchanger networks can be converted into normal parameter optimisation problem by fixing its potential topology or structure.

This fixed potential topology strategy is widely used in mathematical programming method for heat exchanger network synthesis. Two issues arise. The first is "how to divide the system into sub-systems" which has been discussed in Chapter 3. The second is "what is a potential match pattern for each sub-system" which will be discussed in this chapter.

4.2.1 Superstructure and Mathematical Model

The superstructure is a typical match pattern for heat exchanger network synthesis. It was proposed by Yee and Grossmann in 1990. Given such a superstructure, mathematical models for heat exchanger network synthesis can be formulated. The optimal design for the heat exchanger network may then be deduced by using mathematical programming within the potential topology.

The superstructure is a stage-wise structure. With the superstructure, the problem is divided into a number of stages. Within each stage, each hot stream is split to match with all cold streams and likewise a cold stream is split to match with all hot streams. Figure 4.1 illustrates the concepts of a two-stage superstructure.

Although, the superstructure is in the form of a spaghetti design, there are significant differences between the superstructure and the "spaghetti" design. First, in a spaghetti design, the number of stages is identical to the number of energy intervals. All matches are vertical matches. In a superstructure, the number of stages is not identical to the number of energy intervals. Second, within any interval, the temperatures at the boundaries in a spaghetti design are fixed for all hot streams or cold streams. By contrast, in a stage of superstructure, the boundary temperature of each stream is not constrained to be equal. The boundary temperatures are treated as variables. This relaxation permits non-vertical or criss-cross matches (Yee and Grossmann, 1990).

The number of stages in a superstructure is normally less than the number of energy interval in a spaghetti design. The design derived from the superstructure usually requires fewer units than the design from spaghetti design.

Normally, if more stages are included in the superstructure, the likelihood of discovering a better solution for the design increases. Clearly, this increase in stages will produce a corresponding increase in the number of alternative match combinations. Unfortunately, an increased number of stages will also increase the number of variables and hence the difficulty for discovering the global optimal solution. Yee and Grossmann (1990) presented a heuristic rule to determine the number of stages in superstructure. They stated that: '*In general, the number of stages required to model the heat integration will seldom be greater than either the number of hot streams or the number of cold streams*'. However, it is necessary to occasionally increase the number of stages to permit designs with minimum energy consumption (Daichendit and Grossmann 1994).

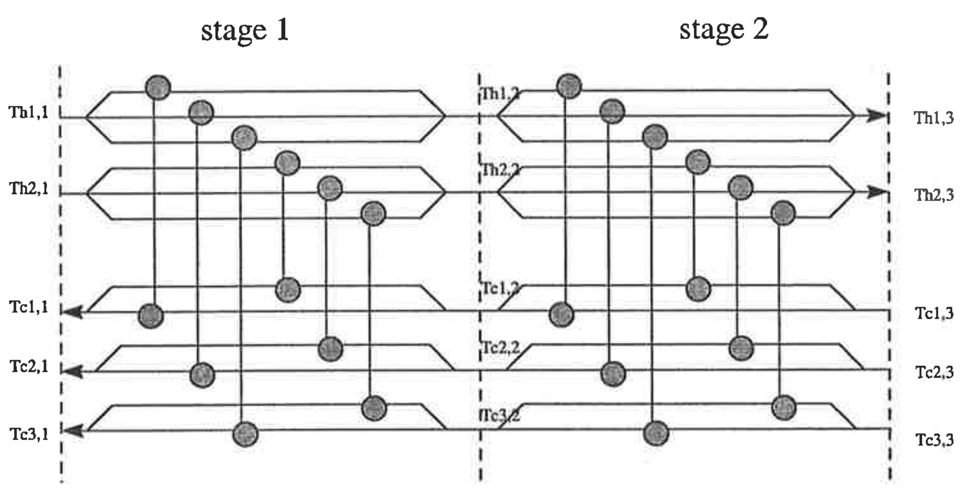


Figure 4.1: Two stages superstructure

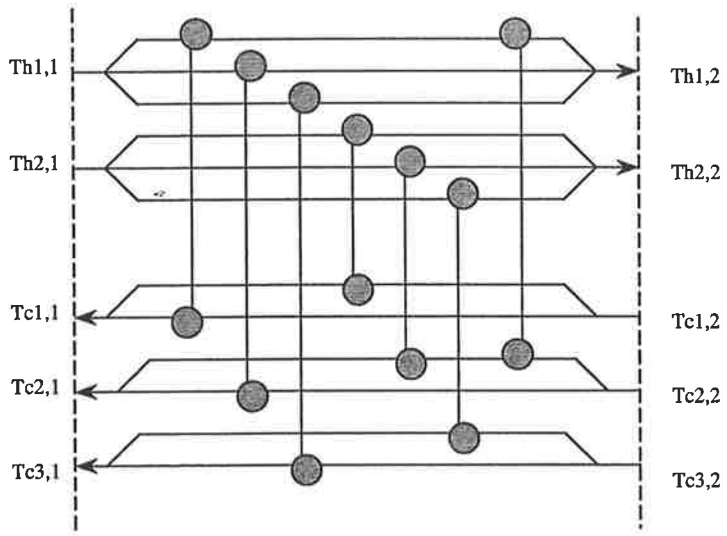


Figure 4.2: Sequential matches

In fact, the superstructure does not embed all potential matches within a stage. For example, neither the sequential match shown in Figure 4.2 or the stream by-pass shown in Figure 4.3 are considered. Stream bypass is seldom required and it is normally not an attractive design option. However, in a very particular situation, stream bypass may help decrease the number of units at the expense of increased area (Wood et. al. 1985).

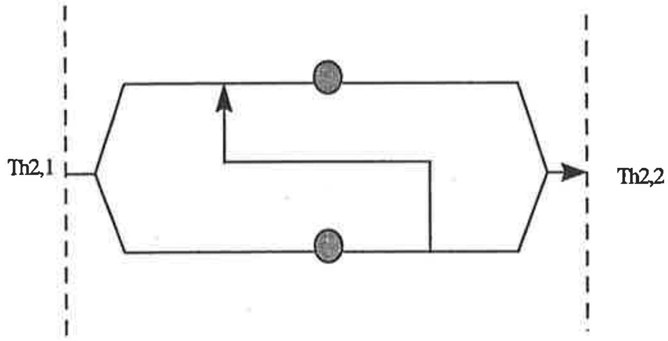


Figure 4.3: Stream by-pass

Despite the fact that the superstructure does not include all potential matches, its simplified structure may significantly reduce the complexity of the match pattern and decrease the difficulty associated with searching.

Using the superstructure and assumptions about parameters, the heat exchanger network synthesis problem can be formulated as follows (Yee and Grossmann, 1990):

Objective function:

$$\min \sum_{i\in HP} CCUqcu_i + \sum_{j\in CP} CHUqhu_j + \sum_{i\in HP}\sum_{j\in CP}\sum_{k\in ST} CF_{ij} z_{ijk} + \sum_{i\in HP} CF_{i,CU}\, zcu_i$$

$$+ \sum_{j\in CP} CF_{HU,j}\, zhu_j + \sum_{i\in HP}\sum_{j\in CP}\sum_{k\in ST}\left(\frac{q_{ijk}}{U_{ij}\, LMTD_{ilk}}\right)^{B_{ij}}$$

$$+ \sum_{i\in HP}\sum_{j\in CP}\sum_{k\in ST}\left(\frac{qcu_i}{U_{i,CU}\, LMTD_{i,CU}}\right)^{B_{i,CU}} + \sum_{i\in HP}\sum_{j\in CP}\sum_{k\in ST}\left(\frac{qhu_j}{U_{j,CU}\, LMTD_{j,CU}}\right)^{B_{HU,j}} \qquad (4.1)$$

Constraints:

$$(TIN_i - TOUT_i)F_i = \sum_{k\in ST}\sum_{j\in CP} q_{ijk} + qcu_i, \qquad i \in HP \qquad (4.2)$$

$$(TOUT_j - TIN_j)F_j = \sum_{k\in ST}\sum_{i\in HP} q_{ijk} + qhu_j, \qquad j \in CP \qquad (4.3)$$

$$(t_{i,k} - t_{i,k+1})F_i = \sum_{j\in CP} q_{ijk} \qquad i \in HP \qquad (4.4)$$

$$(t_{j,k} - t_{j,k+1})F_j = \sum_{i\in CP} q_{ijk} \qquad j \in CP \qquad (4.5)$$

$$TIN_i = t_{i,1}, \qquad i \in HP \qquad (4.6)$$

$$TIN_j = t_{j,NOK+1}, \qquad j \in CP \qquad (4.7)$$

$$t_{i,k} \geq t_{i,k+1}, \qquad k \in ST, \qquad i \in HP \qquad (4.8)$$

$$t_{j,k} \geq t_{j,k+1}, \qquad k \in ST, \qquad j \in CP \qquad (4.9)$$

$$TOUT \leq t_{i,NOK+1}, \qquad i \in HP \qquad (4.10)$$

$$TOUT \geq t_{j,1}, \qquad j \in CP \qquad (4.11)$$

$$(t_{i,NOK+1} - TOUT_i)F_i = qcu_i, \qquad i \in HP \qquad (4.12)$$

$$(TOUT_j - t_{j,1})F_j = qhu_j, \qquad j \in CP \qquad (4.13)$$

$$q_{ijk} - \Omega z_{ijk} \leq 0, \qquad i \in HP, \; j \in CP, \; k \in ST, \qquad (4.14)$$

$$qcu_i - \Omega zcu_i \leq 0, \qquad i \in HP \qquad (4.15)$$

$$qhu_j - \Omega zhu_j \leq 0, \qquad j \in CP \qquad (4.16)$$

$$z_{ijk} = 0,1,$$

$$zcu_i = 0,1,$$

$$zhu_j = 0,1,$$

Where:

Index:

i: hot process or hot utility

j: cold process or cold utility

k: index for stage 1,...NOK and temperature location 1,...NOK +1

Sets:

HP={i | i is a hot stream}

CP={j | j is a cold stream}

HU: hot utility

CU: cold utility

ST: {k | k is a stage in the superstructure, k=1, •••, NOK}

Objective function:

Parameters:

TIN: supply temperature of a stream

TOUT: target temperature of a stream

F: heat capacity flow rate

U: overall heat transfer coefficient

CCU: cost coefficient of cold utility

CHU: cost coefficient of hot utility

CF: cost for installation of a unit

C: cost coefficient for unit

B: exponent in the cost law of the unit

NOK: the number of the stages

Ω: upper bound for heat exchanged by an unit

Variables:

q_{ijk} : heat exchanged between hot stream I and cold stream j in stage k

qcu_i : heat exchanged between hot stream I and cold utility in stage k

qhu_j : heat exchanged between cold stream j and hot utility in stage k

$t_{i,k}$: hot stream temperature at the end of the stage k

$t_{j,k}$: cold stream temperature at the end of the stage k

z_{ijk} :binary variable to denote existence of match (I,j) in stage k

zcu_i :binary variable to denote a cooler existing in hot stream I in stage k

zhu_j :binary variable to denote a heater existing in cold stream j in stage k

Clearly, this mathematical model (based on the superstructure) is highly complex. The global optimal solution can not be guaranteed especially if the problem dimensionality is large.

To reduce this complexity, a simplified superstructure is proposed and will be discussed in the following sections. The mathematical model (match-selection model) for the simplified superstructure is applied independently to each sub-system rather than to the whole system. This feature significantly reduces the size of problem.

4.2.2 A New Match Pattern -A Simplified Superstructure

For a network, several alternative designs can normally be found to achieve near optimal total annual cost. Designs which achieve near-optimal cost constitute an optimal design set. The individual designs within this set may exhibit significant differences in topology and the number of heat exchangers.

The failure of mathematical programming methods for industrial sized problems is partly caused by the complicated potential match pattern which results in a complex mathematical model. Clearly, this difficulty may be reduced if the potential match pattern, used to construct the mathematical model, is simplified.

The work of Yee and Grossmann (1990) confirms that "*a cost optimal design usually does not require a large number of exchangers, meaning that a particular stream does not exchange heat with many streams*". This observation suggests that a cost-optimal design normally possesses a simple structure and has been confirmed by numerous case studies.

A key goal of this work is to define a simple structure which is included in the optimal design set.

For a given set of hot streams and cold streams, the simplest possible structure is a pair-wise matching: each stream is only involved in a single process-process match within each stage or sub-system. Neither stream splitting nor sequential matches are allowed. This match pattern is called a simplified superstructure.

Figure 4.4 illustrates an example of a simplified superstructure. The system is composed of two hot streams and two cold streams. If each stream only participates once in process-process matching, the simplified superstructure has two possible figures as shown in Figure 4.4 (a) and Figure 4.4 (b). In Figure 4.4 (a), hot stream h1 matches with cold stream c1. Hot stream h2 matches with cold stream c2. No other matches are allowed. In Figure 4.4 (b), hot stream h2 matches with cold stream c1. Hot stream h1 matches with cold stream c2. No other matches are permitted.

To reduce the complexity and number of variables within a sub-system, the partition temperatures of streams are fixed for the hot streams or cold streams. Fixed partition temperatures for streams are unrealistic constraints in the real designs. Clearly, the partition temperatures for individual streams may differ. This has been proved by many cases. To correct this simplification, each partition temperature will be revised by optimising the partitioning temperatures in the latter stages of design.

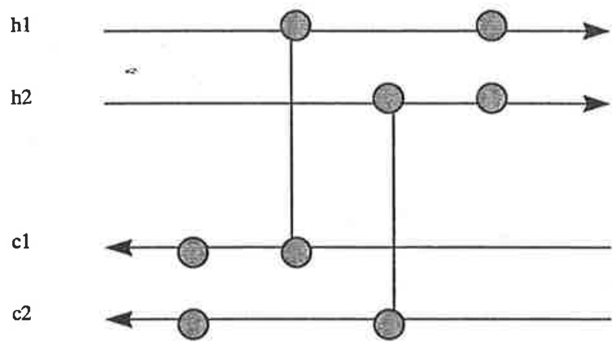
For a heat exchanger network, many alternative simplified superstructures exist. In general, for a system with m hot streams and n cold streams, the number of alternatives is:

$$K_{max}(K_{max-1}) \cdots (K_{max}+1-K_{min})$$

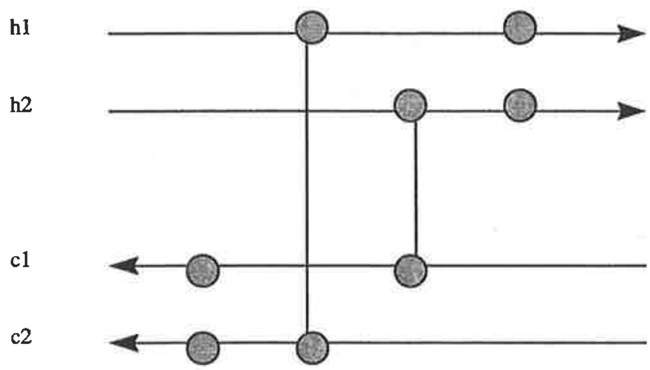
where:

$K_{max}=\max(m,n)$

$K_{min}=\min(m,n)$



(a)



(b)

Figure 4.4: An example of the simplified superstructure

4.3 Match Pattern for A Simple Match

4.3.1 A General Single Match Pattern

In the simplified superstructure, each stream is constrained to participate in a single process-process match. This significantly reduces the complexity of a match pattern and it produces a design with no interaction between the individual matches. This lack of interaction makes it possible to design each individual match independently. Figure 4.5 illustrates the simplest match pattern composed of a single hot and cold stream.

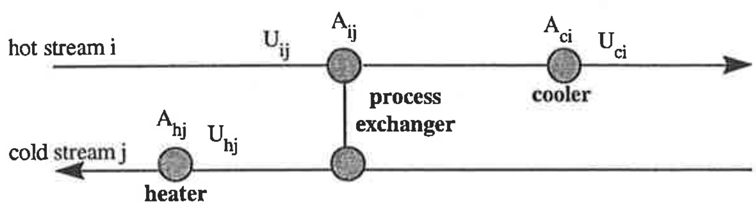


Figure 4.5: The simple match pattern between a hot stream and a cold stream

To evaluate this individual match quantitatively, a cost model is employed. For a match with a hot stream i and a cold stream j, the cost for this single match is referred as a cost index $Cost_{ij}$ and may be defined and evaluated as follows:

$$Cost_{ij} = Cost\_h_{hu} + Cost\_c_{cu} + Cost\_p_{ij} \quad (4.17)$$

$$p_{ij} = R(c_{ij} + b_{ij} A_{ij}^{B_{ij}}) \quad (4.18)$$

$$p_{hu} = CHUQ_{hj} + R(c_h + b_h A_{hj}^{B_h}) \quad (4.19)$$

$$p_{cu} = CCUQ_{ci} + R(c_c + b_c A_{ci}^{B_c}) \quad (4.20)$$

$$R = \frac{r(1+r)^n}{(1+r)^n - 1} \qquad (4.21)$$

where

$Cost_{ij}$: cost index for the stream match

c_{cu}: fixed charge for cooler

c_{hu}: fixed charge for heater

c_{ij} : fixed charge for heat exchanger

$Cost\_c_{cu}$: cost penalty for not ticking off the hot stream

$Cost\_h_{hu}$: cost penalty for not ticking off the cold stream

$Cost\_cpi_{ij}$: capital cost for heat exchanger

CCU : cost of cold utility

CHU : cost of hot utility

b_h , B_h : cost coefficients for heater

b_c , B_c : cost coefficients for cooler

b_{ij} , B_{ij} : cost coefficients for heat exchanger

$Area_{ij}$: area of the heat exchanger

$Area_{ci}$: area of the cooler

$Area_{hj}$: area of the heater

Q_{ci}: cold utility used in cooler

Q_{hj}: hot utility used in heater

R: annual recovery factor

r: annual interest rate

n: plant life time

Equation 4.17 presents a typical cost evaluation for a single match with only utility and capital cost of the exchangers considered. It is easily modified to include more detailed costs. For example, the cost for piping and pumping the stream may be considered, if the locations of units and relevant cost data are available.

Different cost formulations will normally produce different optimal designs. Hence, rigorous cost laws are critical to match selection for the design. Unfortunately, the cost formulation is usually not rigorous for automatic HEN synthesis tools. This simplification may cause the search to focus on an incorrect location for the optimum solution. This problem is one of the reasons for the limited industrial use of automatic HEN synthesis tools (Nielsen et al , 1997).

4.3.2 A Single Match Pattern Starting from the Partition Point

The match pattern proposed in Figure 4.5 represents the normal match situation. The heater is placed on the left of the network and cooler is placed on the right of the network. However, following problem decomposition into sub-systems, the sub system above the pinch or partition temperature ideally requires only hot utility whilst the sub system below the pinch or partition temperature requires only cold utility. Unfortunately application of the previous match pattern to each sub-system will produce criss-cross matches for the remaining parts of design (see Figure 4.6), since the heater and cooler are placed on different sides. To avoid criss-cross matches, designs for both sub-systems will start from the pinch or partition temperature and this will allow the heater and cooler are positioned on the same side. Figure 4.7 shows the match patterns for both sub systems above the partition temperatures and below the partition temperatures. The match patterns for sub-systems differ from the match pattern for the root system shown in Figure 4.5. To start the match from the pinch or partition point, the criss-cross match for the remaining parts in Figure 4.6 is avoided (see Figure 4.8).

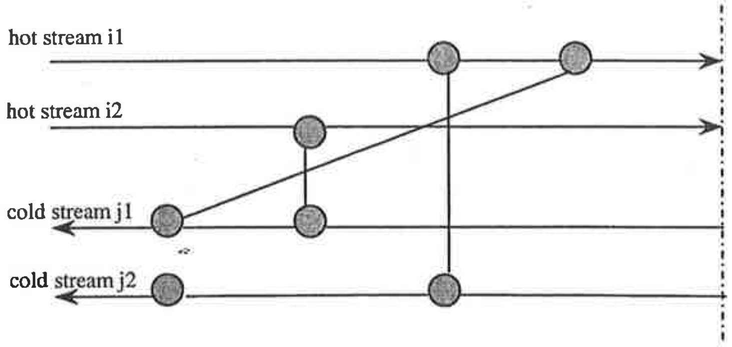
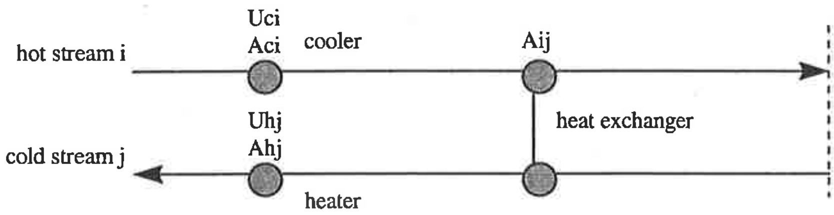
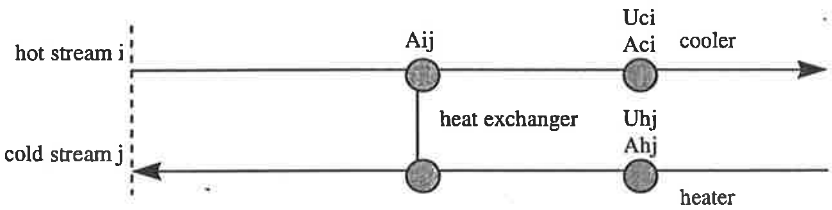


Figure 4.6: Criss-cross match for the remaining parts



(a) above the partition points



(b) below the partition points

Figure 4.7: Match patterns for sub-systems

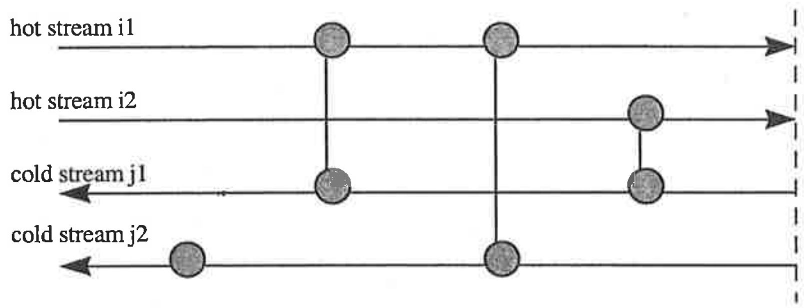


Figure 4.8: Match without criss-cross

4.4 Match Selection Model for Initial Design

The initial design constructs the backbone or basic topology for the design. It plays an important role in the network synthesis. Based on the proposed simplified superstructure, a match selection model for initial design is presented. The initial design is a cost optimal simplified superstructure.

4.4.1 The Cost Optimal Match and the Initial Design

Since no interaction exists between individual matches in the initial design, single matches in the initial design are independent of each other. The initial design becomes the simple combination of these potential matches.

If Mset is denoted as a simplified superstructure or a candidate of the initial design, we have:

$$Mset = M_{i1,j1} \cup M_{i2,j2} \cup \cdots\cdots \cup M_{i,j} \cup \cdots\cdots \cup M_{in,jn}$$

M_{ij} is a single potential match, $i \in H$, $j \in C$

$i1 \neq i2 \neq \cdots\cdots i \cdots\cdots \neq in$

$j1 \neq j2 \neq \cdots\cdots j \cdots\cdots \neq jn$

n = max(No_h, No_c)

No_h: the number of the hot streams

No_c: the number of the cold streams

The total annual cost of the initial design may be considered as the sum of the individual matches. To achieve a cost optimal design for the initial design, each individual match must process minimum total annual cost as well. Based on this relationship between individual matches, potential matches in the initial design could be divided into separate individual matches and optimized individually.

Supposing Mset' is a simplified superstructure which consists of cost optimal individual matches, we have

$$Mset' = M_{i1,j1}' \cup M_{i2,j2}' \cup \cdots\cdots \cup M_{i,j}' \cup \cdots\cdots \cup M_{in,jn}'$$

M_{ij}' is a single cost optimal potential match with a match pattern for a simple match, $i \in H, j \in C$

$i1 \neq i2 \neq \cdots\cdots i \cdots\cdots \neq in$

$j1 \neq j2 \neq \cdots\cdots j \cdots\cdots \neq jn$

n = max(No_h, No_c)

No_h: the number of the hot streams

No_c: the number of the cold streams

To achieve the minimal total annual cost for each potential match, the energy recovered by heat exchanger in the individual match is optimised. The value of the total annual cost for each potential match is stored into a match matrix used by the match selection model.

4.4.2 Match Matrix

The match matrix is used to store the cost value for each cost optimal potential match. For a cost optimal match between hot stream i and cold stream j, the cost detailed in equation 4.17 is stored as the element a_{ij} of the match matrix.

In the simplified superstructure, the match matrix is always square. When the numbers of hot and cold streams are not equal, several hot or cold utility streams will be included in the hot stream list or cold stream list to balance the stream numbers. Three situations may occur :

- If the number of cold streams m equals the number of hot streams n, then utilities are not used to balance the stream number. The match matrix is described by:

streams	h_1	h_2	.	h_n
c_1	a_{11}	a_{12}	.	a_{1n}
c_2	a_{21}	a_{22}	.	a_{2n}
.	.	.	.	.
c_n	a_{n1}	a_{n2}	.	a_{nn}

If the number of cold streams and the number of hot streams differ, a match balance needs to be performed to make the match matrix square. There are two cases which need to be discussed.

- Case 1: m > n, the number of cold streams m exceeds the number of hot streams n. (m-n) hot utilities are added to the list of hot streams to balance the number of cold streams. The value of the cost indicator for a match between hot utility and a cold stream equals the cost if the entire cold stream is heated by hot utility. The match matrix for this situation becomes:

streams	h_1	h_2	.	h_n	h_{u1}	.	h_{um-n}
c_1	a_{11}	a_{12}	.	a_{1n}	a_{1n+1}	.	a_{1m}
c_2	a_{21}	a_{22}	.	a_{2n}	a_{2n+1}	.	a_{2m}
.	.	.	.	.	.	.	.
c_m	a_{m1}	a_{m2}	.	a_{mn}	a_{mn+1}	.	a_{mm}

where:

h_i $i = 1,n$ hot streams

$i = u_1, u_{m-n}$ hot utilities

c_i $i = 1,m$ cold streams

- Case 2 : m < n, the number of cold streams m is less than the hot streams number n. (n-m) cold utilities are added to the list of cold streams to balance the hot streams. The value of the cost indicator for a match between cold utility and hot stream equals the cost that the complete hot stream is cooled by utility. The match matrix for this situation is shown below.

streams	h_1	h_2	.	h_n
c_1	a_{11}	a_{12}	.	a_{1n}
c_2	a_{21}	a_{22}	.	a_{2n}
.	.	.	.	.
c_m	a_{m1}	a_{m2}	.	a_{mn}
c_{u1}	a_{m+11}	a_{m+12}	.	a_{m+1n}
c_{un-m}	a_{n1}	a_{n2}	.	a_{nn}

where:

h_i $i = 1,n$ hot streams

c_i $i = 1,m$ cold streams

$i = u_1,u_{n-m}$ cold utilities

4.4.3 The Match Selection Model for Initial Design

Using the simplified superstructure and the cost optimal individual matches, a match selection model for initial design may be formulated.

The binary variable x_{ij} defines a potential match between hot stream i and cold stream j. x_{ij} equals one if a match exists and conversely x_{ij} equals to zero if match does not exist. As each stream is restricted to a single process-process match, then:

$$\sum_{i=1}^{l} x_{ij} = 1 \qquad j = 1,l \tag{4.22}$$

and

$$\sum_{j=1}^{l} x_{ij} = 1 \qquad i = 1,l \tag{4.23}$$

Assuming the cost index for match matrix is a_{ij}, the total annual cost of a possible match combination is:

$$\sum_{i=1}^{l}\sum_{j=1}^{l} a_{ij} x_{ij} \tag{4.24}$$

The match selection model for the initial design is now a simple assignment IP (integer programming) problem:

$$\min \quad \sum_{i=1}^{l}\sum_{j=1}^{l} a_{ij}x_{ij} \qquad (4.25)$$

constraints:

$$\sum_{i=1}^{l} x_{ij} = 1 \qquad j = 1,l$$

$$\sum_{j=1}^{l} x_{ij} = 1 \qquad i = 1,l$$

$$x_{ij} = 0,1 \qquad i,j = 1,l \qquad (4.26)$$

$$l = \max(m,n)$$

where:

a_{ij} is the element of the match matrix.

x_{ij} is a binary:

x_{ij} equals one if match exists between cold stream i and hot stream j.

x_{ij} equals zero if match does not exist between cold stream and hot stream j

The method of location an initial design consists of two steps:

- Optimising each potential match to determine the element of the cost matrix.
- Solving the match selection model (IP).

This match selection model is a simple integer programming (IP). It is a classical assignment problem and is readily solved by many efficient algorithms available such as well-known Hungarian algorithm. The solution is obtained without any ambiguities. The difficulty caused by NLP, MINLP, MILP problems is avoided. Since the matches for the initial design are decided by this match selection model, the problems and uncertainties caused by heuristic rules may be avoided and design quality will be improved. The design by this match selection model depends on method rather than the designer.

4.4.4 Illustrative Examples

Two simple examples are provided to demonstrate the match selection model for an initial design.

4.4.4.1 Example one

This problem contains three hot streams and three cold streams. The relevant stream data and cost coefficients can be obtained from the case study one in Chapter 5. In the root node design, each hot stream may match with each cold stream. This produces 9 (3×3) potential matches. The costs for these 3×3 potential matches are presented in the match matrix (Table 4.1). Based on this match matrix, the match selection model produces a solution with the binary x_{11}, x_{22} and x_{33} equal to unity. That solution implies an initial design for the root node involving match h1-c1, h2-c2 and h3-c3. The match h3-c3 is a zero duty match (Figure 4.9). In fact, this example is sufficiently simple that a solution could easily be discovered by enumeration rather than by the IP.

Table 4.1: Match matrix for the root node

	h1	h2	h3
c1	99336	141667	281090
c2	81622	79314	168194
c3	120126	151942	160559

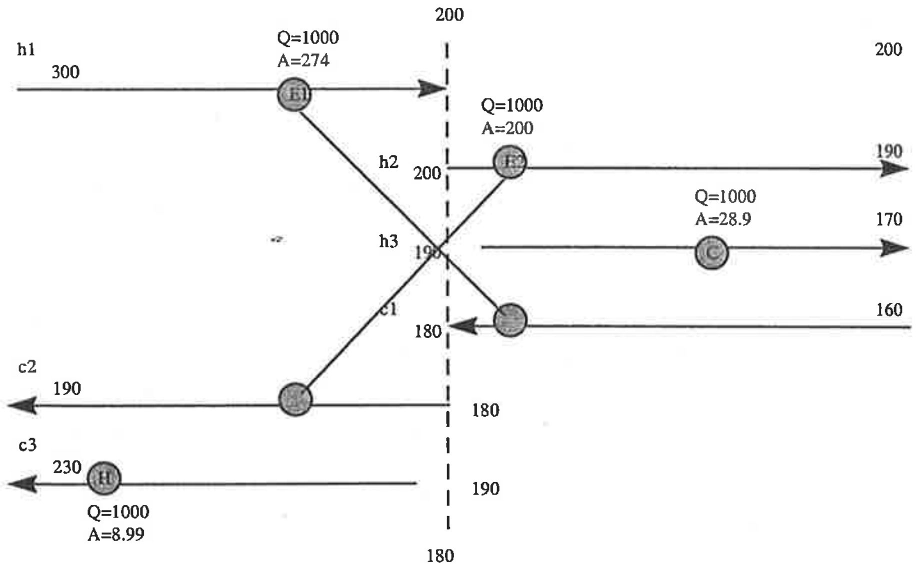


Figure 4.9: The initial design for the root node

4.4.4.2 Example two

This problem involves three hot streams and two cold streams. The relevant stream data and cost coefficients may be obtained from the case study 2 in Chapter 5. Since the number of cold stream is one less than the number of the hot streams, a single cold utility is added in the list of cold streams to balance the matrix.

Table 4.2: Match matrix for root node

	h1	h2	h3
c1	17805	14969	7355
c2	41634	39190	27628
cold utility	5911	2332	2994

The costs for the potential matches are presented in the match matrix (Table 4.2). In row three, the matrix elements are the costs given that the hot stream is cooled solely by cold utility. The optimal solution from the match selection model sets the binary variables index x_{11}, x_{23} and x_{32} to unity. Hence, an initial design involves matches h1-c1 and h3-c2 (Figure 4.10). Hot stream h2 does not participate in any process-process stream match and is cooled using cold utility.

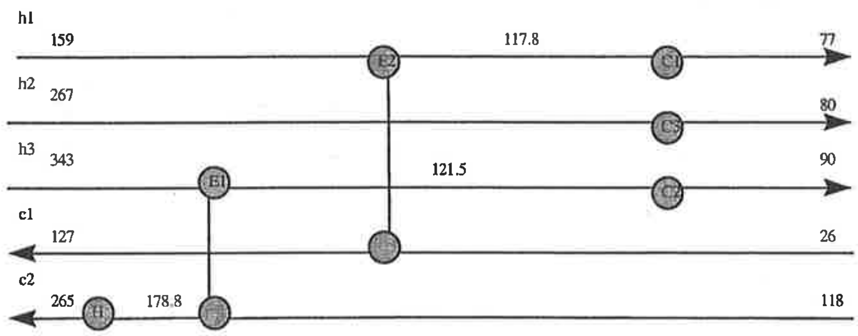


Figure 4.10: The initial design for the root node

4.5 Scaling - Preferred Matches and Forbidden Matches

In real world problems, the designer may face a variety of constraints imposed by safety, layout and distances between two units and so on. As a consequence, potential matches between some streams may be preferred or even forbidden. Such situations cause considerable difficulty particularly for evolutionary design. However, they can be simply handled in the proposed method using scaling of the cost of potential matches. The logic of this is outlined below.

Consider a candidate match between stream i, j. The cost index a_{ij} maybe redefined as

$$a_{ij} = a'_{ij} * S_{ij}$$

a_{ij} : scaled cost index

a'_{ij} : unscaled cost index

S_{ij}: scaling

Here, S_{ij} is a weighting factor on the cost index. Its value depends on the match situation. If the match is a normal one, then S_{ij} is equal to one. If the match is preferred, the scaling S_{ij} is assigned a value less than one. This will increase the possibility of the match to be selected due to the decrease of the cost index. If a match between the two streams is unattractive, then the scaling factor S_{ij} is assigned a value more than one. This will decrease the possibility of the match to be selected due to the increase of the cost index. In the extreme case of a forbidden match, the scaling S_{ij} is set to an arbitrarily large value. Its large cost index will then ensure that the forbidden match is not selected in the initial design.

4.6 Sequential Matches

Another common scenario that needs to be addressed is sequential matching. Suppose that a system has only a single hot stream or cold stream, the problem must now involve sequential matching. Sequential match problems may be designed by inspection. Alternative designs only differ in the order of the matches.

The first issue to be addressed in the sequential match problem is to discover a match sequence to recover maximum energy, this sequence may then be adjusted to reduce the capital investment. It may be difficult to design the sequential matches without considering the impact of supply temperatures, target temperatures and enthalpy change of streams on the design. In some cases, after several matches are selected, other streams may not be available to participate in process-process matching because the driving forces may become unfavourable or unfeasible. However, this may be avoided if the matches are arranged in a suitable match order.

Stream data, which impact on the sequential matches, include supply temperatures of the streams, target temperatures of streams and the changes in the enthalpy of the streams. Normally, the hot stream with smaller target temperature, smaller supply temperature and smaller enthalpy change is preferred to match on the right side of system. The cold stream with larger target temperature, larger supply temperature and smaller enthalpy change is preferred to match on the left side of system.

Two rules are recommended for situations where sequential matches occur.

If the single stream is cold stream:

- Match hot streams with low target temperatures first;
- Match hot streams with low supply temperatures first;
- Match hot streams with smaller enthalpy change first;

Apply the converse of these heuristics if the single stream is a hot stream:

In general, sequential matching is easily solved by inspection. However, the previous rules can be incorporated into the match-selection model using the scaling concept. Again for a preferred match, the scale factor is less than unity.

A quantitative method for determining the scale factor has been developed. Suppose the single stream is cold stream with a number of potential hot streams. Normally, the matching commences from the colder side of the single stream and hot streams with higher supply temperatures and/or target temperatures are less attractive. This procedure can be enforced by scaling on the basis of temperature ratios as follows:

$$scale1 = T_{supply,i} / T_{supply,min}$$

$$scale2 = T_{target,i} / T_{target,min}$$

$$scale = scale1 * scale2$$

where:

$T_{supply,i}$: the supply temperature of hot stream i

$T_{supply,min}$: the minimum supply temperature of hot streams

$T_{target,i}$: the target temperature of hot stream i

$T_{target,min}$: the minimum target temperature of hot streams

Conversely, if the single stream is hot stream:

$$scale1 = T_{supply,max} / T_{supply,i}$$
$$scale2 = T_{target,max} / T_{target,i}$$

$$scale = scale1 * scale2$$

where:

$T_{supply,i}$: the supply temperature of cold stream i

$T_{supply,max}$: the maximum supply temperature of cold streams

$T_{target,i}$: the target temperature of cold stream i

$T_{target,max}$: the maximum target temperature of cold streams

4.7 Evolution of the Initial Design

The initial design, which prohibits interaction and provides a simple and basic topology, may be considered as the starting point for the optimal search. Further opportunities may exist to evolve the design. The topology of the network is altered and the design is gradually evolved into the optimal design set. The procedures and options for evolution are discussed in the following sections.

4.7.1 The Remaining Parts of the Problem

Following the initial design, several hot or cold streams (or parts thereof) may not be involved in process-process energy exchange. These streams will be heated or cooled by utilities in the initial design. For example, consider the initial design shown in Figure 4.11 for a five stream problem, two process-process matches exist. In addition, one heater and three coolers are required. The sections of streams not involved in process - process exchanger constitute the remaining parts of the design (Figure 4.12).

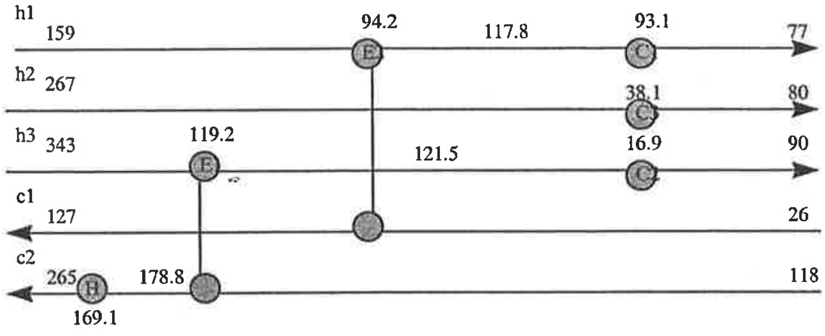


Figure 4.11: An example of an initial design

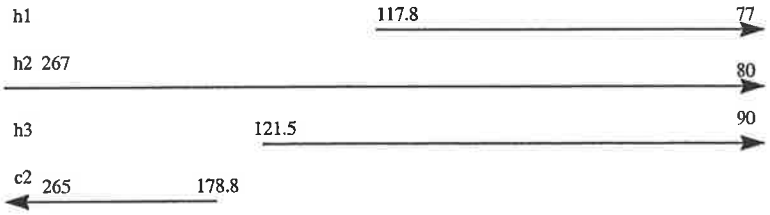


Figure 4.12: The remaining parts of the initial design

There will normally be opportunities to reduce the cost for the remaining parts of design. These streams may be analysed and designed as a new problem. For example in Figure 4.12, hot stream h2 can match with the remaining parts of cold stream c2. This match recovers energy from the hot stream 2 and further reduces the total annual cost. The combination of the initial design and the remaining parts design is illustrated in Figure 4.13.

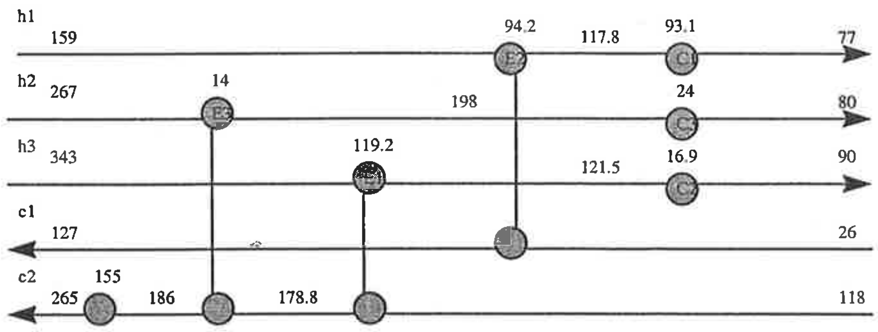


Figure 4.13: Combination of the two designs

4.7.2 Stream Splitting

In the initial design, each stream is constrained to a single process match. However, following evolution of the remaining parts of the system, several cold (or hot) streams may match with more than one hot (or cold) stream. This is called multiple matching. Figure 4.14 illustrates an example of stream splitting. Prior to this stream splitting, the design costs $47,610 (Figure 4.13). The splitting reduces the cost to $46,790 (Figure 4.14).

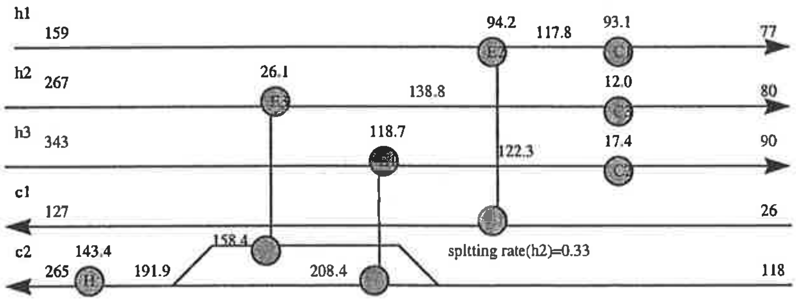


Figure 4.14: An example of stream splitting

Given such a situation, stream splitting may be used to alter the driving forces to reduce the total annual cost. Stream splitting will only be adopted if it results in cost savings.

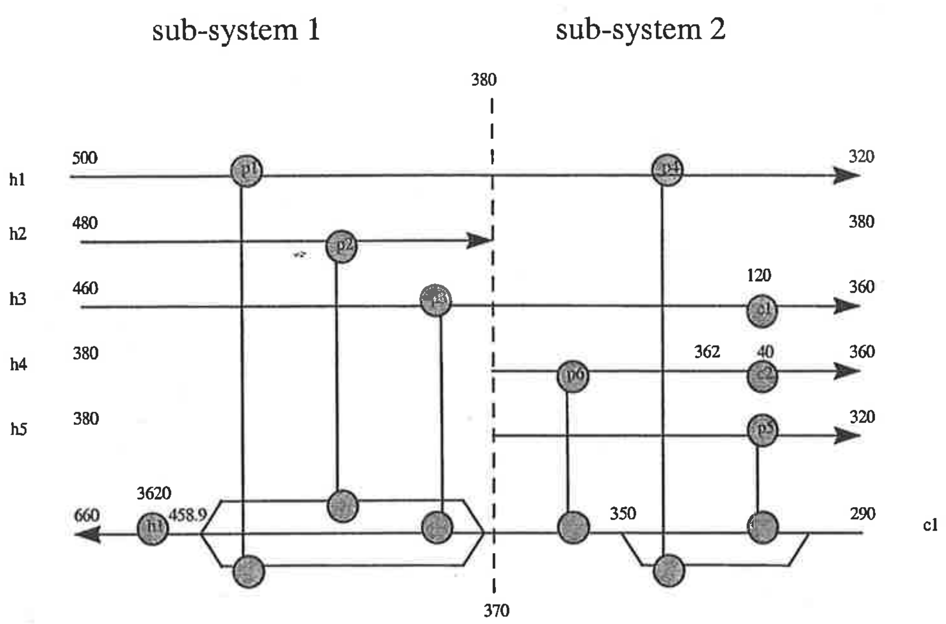


Figure 4.15: Stream splitting in a network

Stream splitting may be contemplated in other circumstances. When a hot or a cold stream matches with multiple cold or hot streams, sequential matching increases the effective supply temperature of the cold stream. The increase of supply temperature may result in a reduction in possible energy recovery for downstream matches. For example, in sub-system1 shown in Figure 4.15, stream c1 is split allowing the energy from three hot streams (h1, h2 & h5) to be fully recovered. If sequential matching was exploited rather than splitting, the temperature of the cold stream c2 after the first match would exceed 380°C. Obviously, the energy content of the remaining two hot streams could not be fully recovered.

4.8 Summary of the Match Selection Procedures

The summary of the match selection procedures for a single node is presented in Figure 4.16.

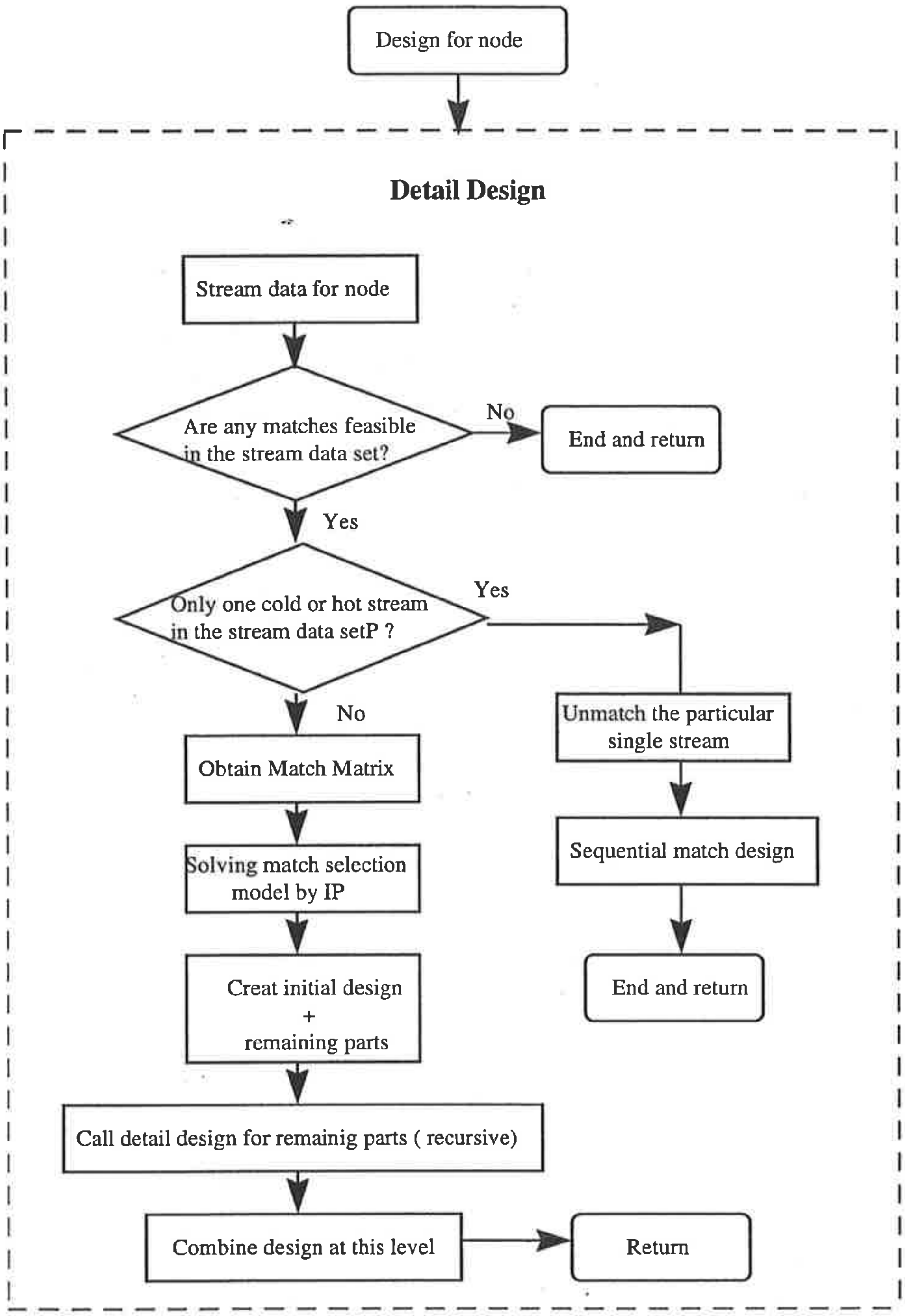


Figure 4.16: Match selection procedures for a single node

4.9 Conclusion

A new match selection method for grassroots design is presented in this chapter. It is simple and straightforward. For each problem, an initial design is discovered by the match selection model developed in this work. The remaining parts of problem, which do not participate in the process-process matches, are considered as a new problem and solved by identical procedure as the initial design. This design procedures are repeated until no feasible matches are available.

Match selection is determined quantitatively by the match selection model rather than by heuristic rules. This alleviates uncertainty, excessive time consumption and inefficiency caused by heuristics rules. The effort for a design is significantly reduced and the final design depends primarily on the method rather than the designer's bias.

The method can easily cope with variant situations, such as forbidden matches or imposed matches. Considerations of safety and layout may be easily incorporated into the design and the final design is more acceptable.

CHAPTER 5

A RECURSIVE SYNTHESIS METHOD FOR COST OPTIMAL DESIGN

5.1 Introduction

In this chapter, the previous concepts will be combined to provide a new design methodology. It is a hybrid method with aspects of evolutionary and mathematical programming methods. The main components are the binary tree decomposition strategy described in Chapter 3 and a match selection procedure summarised in Chapter 4.

Using the decomposition strategy, the method can handle problems with substantially different film heat transfer coefficients and equal film heat transfer coefficients using an identical set of design rules. This differs from the traditional methods where different design rules are normally required (Gundersen and Grossmann, 1990, Zhu et. al. 1995).

The match selection criteria proposed in Chapter 4 means that the method can select matches simply and efficiently. The difficulties and inefficiencies (particularly in evolution) caused by heuristic rules in the Pinch Design Method are avoided using the match selection model. The match selection model is a simple zero-one integer programming problem and it is easily solved, even for extremely large problems, as an assignment problem.

To reduce complexity and the number of variables, the partition temperatures of streams in the simplified superstructure are initially fixed for hot streams or cold streams within each sub-system or node. This partition temperature constraint for individual streams is later relaxed and optimisation of partition temperatures is performed as part of network synthesis. This optimisation corrects any inaccuracy in the trade-off between the capital investment and energy cost.

5.2 A Recursive Design Algorithm

In the new method, system decomposition is easily understood as a binary tree structure. The design starts at the root of the tree where the problem is treated as an entity without decomposition. Further decomposition for each node depends on the requirements and it is normally decided by the cost dominant component. When all the leaf nodes in the binary tree are no longer decomposed, the binary tree for the problem is complete.

The design for each node is obtained recursively. The designs for two child nodes are combined to constitute a design for their parent node. This process starts from the leaf nodes and ends with the design for the root node, thereby constructing the design for the problem.

Figure 5.1 is a simple example showing how the design for heat exchanger network is obtained in the new method. The binary tree has three levels and four leaf nodes 1-1, 1-2, 2-1, and 2-2. The four leaf nodes no longer require the decomposition and their designs form the designs for their parent nodes (Designs for node 1-1 and node 1-2 are combined to form the design for their parent node 1. Designs of 2-1 and 2-2 are combined to form the design for their parent node 2). The final design for the problem which is the design for the root node is constructed by the designs of nodes 1 and 2.

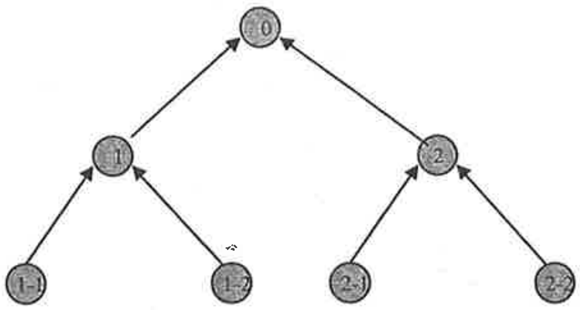


Figure 5.1: An illustration of a recursive design

5.3 Optimisation of Partition Temperatures

The design from the evolutionary methods may be treated as the initial values for the optimisation problem. It is formulated as MINLP or NLP problem and further optimised using mathematical programming method. This optimisation strategy is considered as one of the ways to incorporate both the evolutionary and mathematical programming methods.

A method which employs this strategy is Zhu et al.'s "block method" (Zhu et al., 1995). In the method, an initial design is found by 'block method" to construct topology for the design. This initial design is then optimised by using MINLP. However, the "block method" normally can not directly produce an initial design, which will be optimised to the cost optimal design. Normally, several alternatives for the initial design are required.

From the view of mathematical programming, although a good initial design could improve the performance of the MINLP programming, it does not overcome the problems the MINLP models may face, such as an excessive number of variables and constraint equations. For example, a five-stream problem may require 38 variables and 67 equations. Using the so-called "Specific Formulation", the problem is reduced to a mathematical model with 5 independent variables, 18 dependent variables and 39 equations (Zhu, 1994).

However, by optimising the partition temperatures, the number of variables, which are optimised, can be reduced to the number of the partition temperatures or even fewer. This reduces the difficulty of the optimisation.

Optimisation of the partition temperatures corrects the unreal simplification employed in the reduced superstructure. The partition temperatures in the simplified superstructure are assumed identical for all hot streams or all cold streams. However, in reality, each individual stream in the design should have its individual partition temperature. To revise this simplifying assumption, optimisation of the partition temperatures is performed after each combination of designs of two child nodes forms the design for their parent node. This optimisation procedure produces differing partition temperatures for individual streams and corrects for any inaccuracy in the trade-off between the capital investment and energy cost.

Since the topology of the pre-optimisation design generated by this new method may be the combination of the optimised designs of the sub systems, the pre-optimal design is likely to be close to the cost optimal design (see case studies) even without the final partition temperature optimisation. The pre-optimal designs also demonstrate Yee and Grossmann's observation that 'a cost optimal design usually does not require a large number of exchangers, meaning that a particular stream does not exchange heat with many streams' (Yee and Grossmann, 1990).

Partition temperature optimisation may be performed on an Excel spreadsheet. As a result, a complicated mathematical model, which involves the dozens of variables and equations, may not be required.

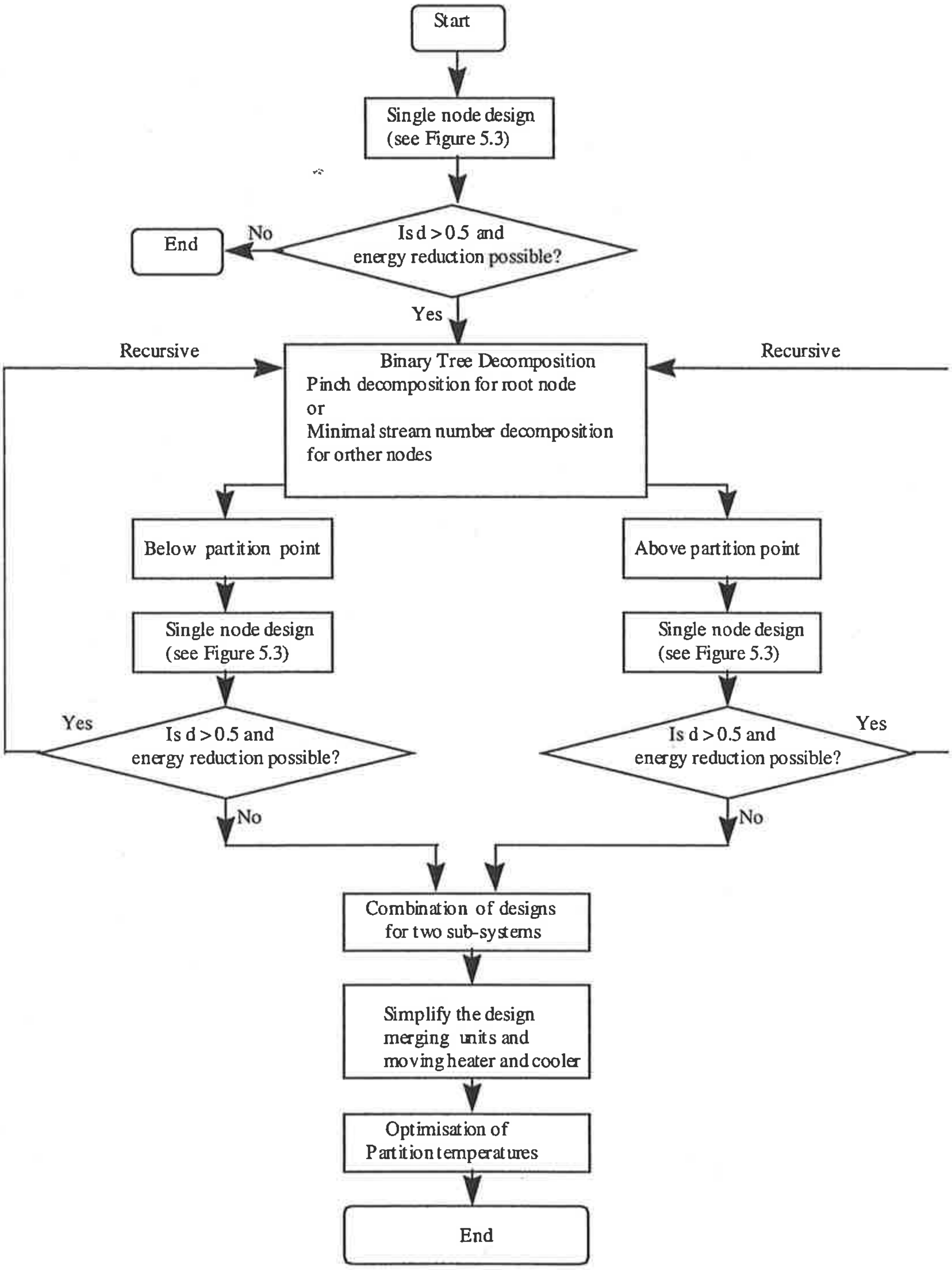


Figure 5.2: Overview of the design algorithm

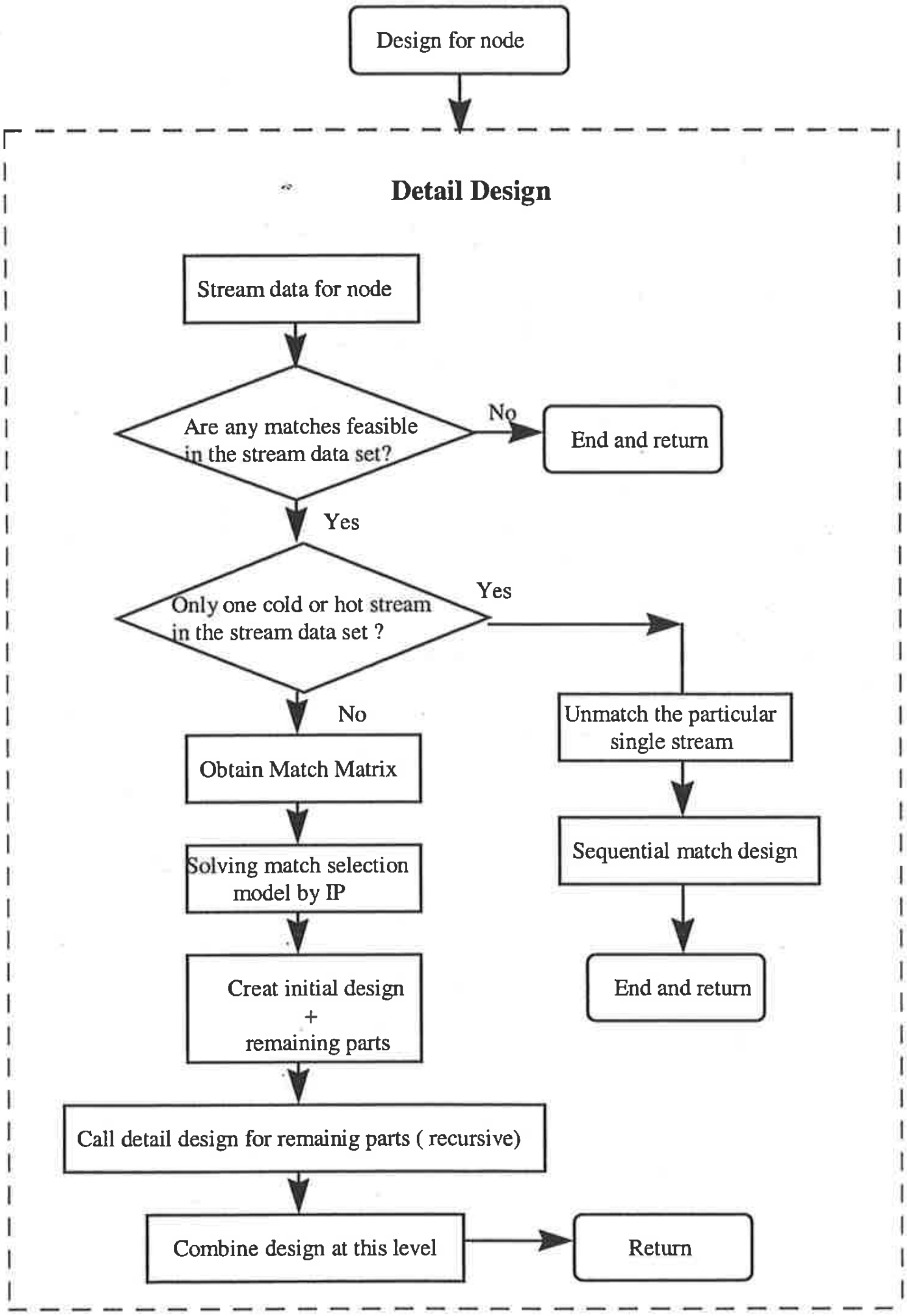


Figure 5.3: Detail design for single node

5.4 Summary of Design Procedures

The logic of the design algorithm for the recursive synthesis method is summarised in Figures 5.2 and 5.3. Figure 5.2 shows the overview of the design algorithm and Figure 5.3 shows the detailed design procedures for a single node.

5.5 Case Studies

Ten case studies will be presented to demonstrate all the facets of the proposed design method. According to their features, the case studies are categorised into three groups: capital-cost dominant problems, energy-cost dominant problems and problem with constraints. Among the ten case studies, cases 1 and 2 are capital-cost dominant problems. Cases 3 to 7 are energy-cost dominant problems, which include the "Aromatic Plant" for using European (energy expensive) and South American (energy cheap) cost models. Case 8 and 9 are problems with constraints.

All case studies will be compared to literature solutions so that the quality of the solution and efficiency of the recursive synthesis method may be demonstrated.

5.5.1 Capital-Cost Dominant Problems

For capital-cost dominant problems, energy cost contributes less than half of the total annual cost. The network tree for such problems consists solely of the root node. Expansion of the tree is unnecessary.

Two case studies are presented to illustrate such problems. Both feature film transfer coefficients that differ by an order of magnitude.

5.5.1.1 Case Study 1

This problem was first proposed by Gundersen et al. (1990) and later studied by Zhu et al. (1995). The relevant stream data are shown in Table 5.1. A key feature of this problem is that the film heat transfer coefficients differ by an order of magnitude. Traditional methods experience difficulties in handing this problem.

The original problem did not include any data on utility cost, plant life time and interest rate. To undertake a cost optimal design, utility cost data, plant life time and interest rate have been assumed. In the first case, plant life time and interest rate are assumed to be 1 year and 0 percent respectively. In the second case, these values are set to 10 years and 10 percent respectively (see page 96).

Table 5.1: Stream data for case study 1

Stream	h1	h2	h3	steam	c1	c2	c3	water
Tin(°C)	300	200	190	350	160	180	190	30
Tout(°C)	200	190	170	350	180	190	230	50
Cp(kW/k)	10	100	50		50	100	25	
h(kW/m^{2}K)	0.1	1	1	4	0.1	1	1	2
Q(kW)	1000	1000	1000		1000	1000	1000	

Exchanger cost ($): $10000+1000A^{0.8}$
Cost of hot utility: $ 110/kW yr.
Cost of cold utility: $ 10/kW yr.

When the Pinch Design Method is applied to this problem, the value of the ΔT_{min} (HRAT) is set at 20 K. Since no match is permitted to cross the pinch, the design shown in Figure 5.4 is discovered (Gunderson et al., 1990). The design requires total area 674 m^2 and annualised capital investment $256,750. Annual utility consumptions are 1000 kW of hot utility and 1000 kW of cold utility.

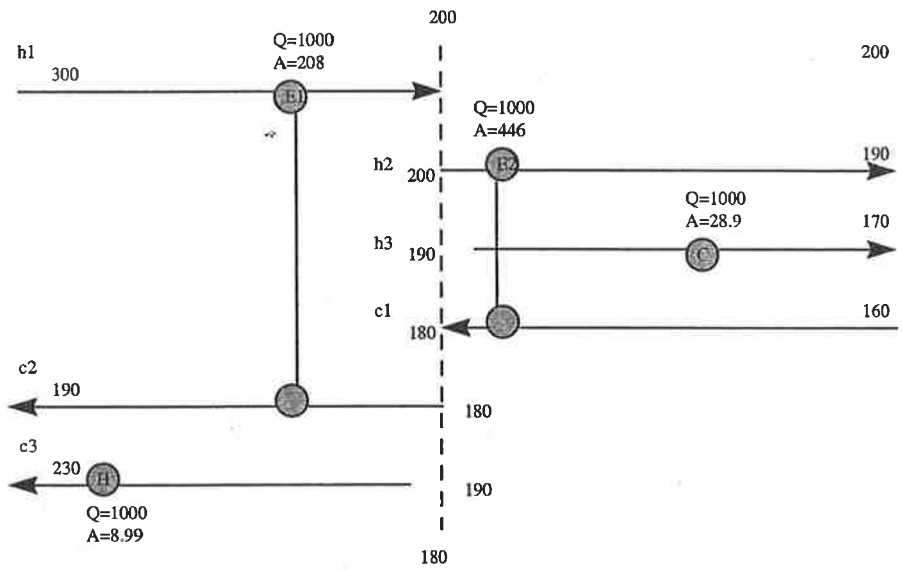


Figure 5.4: Design for case study 1 with HRAT = 20 K

When the film heat transfer coefficients differ significantly, vertical transfer design (imposed by the pinch) no longer provides the lowest total area and investment cost. This is demonstrated by the design obtained by allowing criss-cross heat transfer across the Pinch (Figure 5.5). In this network, the total area decreases from 674 to 494 m^2. The total annualised capital investment is reduced from $256,750 to $211,120. Unfortunately, the design in Figure 5.4 can not be evolved to the design in Figure 5.5 (Gunderson et al., 1990).

The key issue is that for systems with significantly different film heat transfer coefficients, strict vertical heat transfer may not result in a low network area and investment cost. Deliberate cross pinch matches may be required to reduce capital cost. Clearly, Pinch decomposition will not produce the optimal design for this problem.

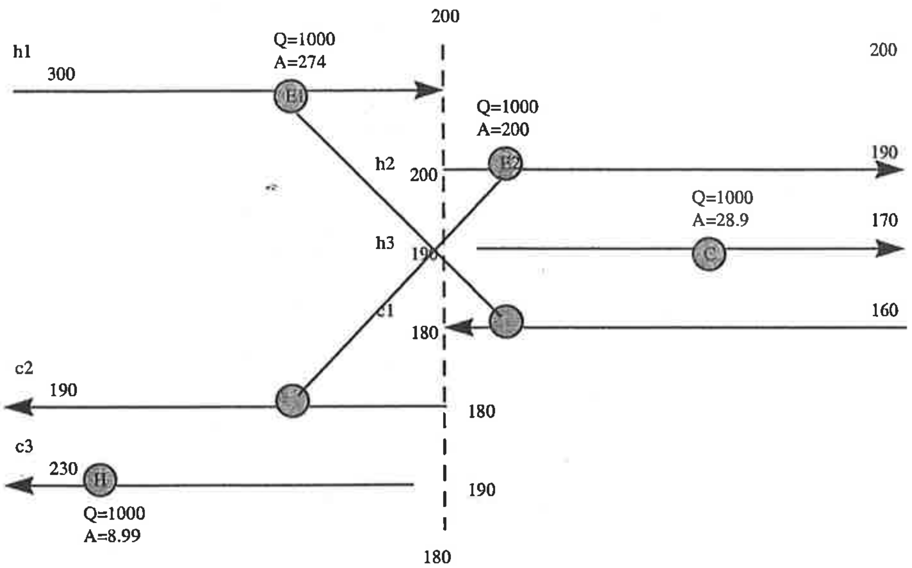


Figure 5.5: Criss-cross design for case study 1 with HRAT = 20 K

Gundersen and Grossmann (1990) solved this problem using mathematical programming. They employed individual stream contributions to the global minimum temperature approach with a modified vertical MINLP model. Unfortunately, the optimal design could not be directly discovered using their criteria. Zhu et al. (1995) proposed an alternative method to find the optimal design. First, they employed diverse pinch approach to generate a set of modified composite curves. Then stream c1 and c3 were shifted across the pinch. Based on this decomposition, an initial design was discovered (Figure 5.6). The optimal design was deduced by evolving this design using MINLP.

By contrast, the design shown in Figure 5.5 may be easily deduced by the proposed recursive design method. Following the design logic of the recursive synthesis method, this problem is identified as a capital-cost dominant problem and a single design for the root node is required.

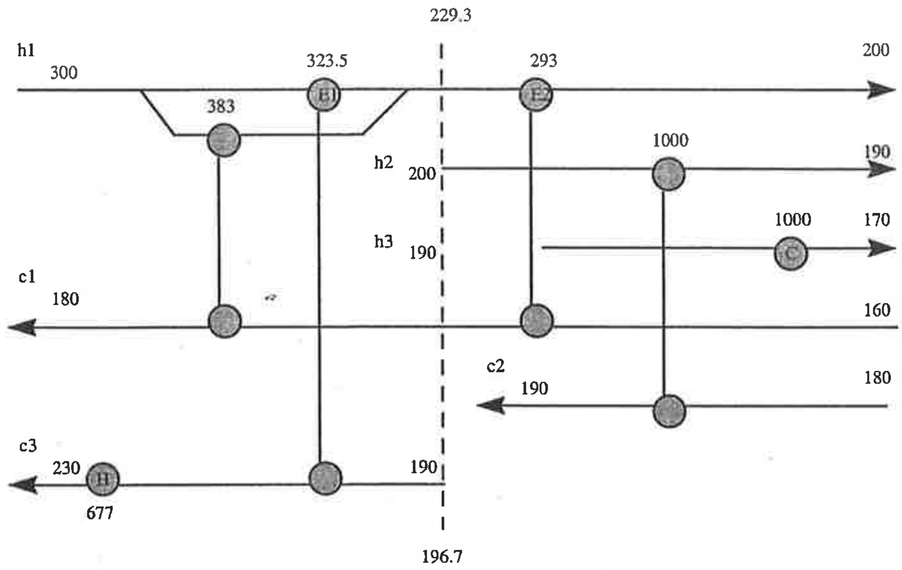


Figure 5.6: The initial design from Zhu et al. (1995)

Design for the root node

In the design for the root node, the system is treated as a single entity and decomposition is not undertaken.

The match matrix for the root node is presented in Table 5.2. It produces an initial design involving matches h1-c1, h2-c2 and h3-c3. The match h3-c3 is an interesting one as the supply temperature of the cold stream c3 equals the supply temperature of the hot stream h3. Clearly energy cannot be transferred between the two streams and as a consequence, h3 and c3 reach their target temperatures by using cold utility or hot utility (Figure 5.5).

The remaining parts of the initial design are the hot stream h3 and the cold stream c3. Further matching is not possible. Hence, this initial design is the final design for this problem. The total annual cost is $339,210 and the energy cost is $120,000. The energy cost is less than 40% of the total annual cost of the design and the problem is a capital cost dominant one. Further decomposition of the root node is unnecessary.

Table 5.2: The match matrix for the root node

	h1	h2	h3
c1	99336	141667	281090
c2	81622	79314	168194
c3	120126	151942	160559

This design is identical to the optimal design illustrated in Figure 5.5. Interestedly, it is discovered in a single step by the new algorithm.

This problem can be used to illustrate another key pointer. Normally, the optimal design for a problem is strongly influenced by the cost laws and associated parameters. Different cost laws may produce different optimal designs. For example, the optimal design illustrated in Figure 5.5 is achieved only when the capital cost for case one is relatively large. If we assume a plant life time of 10 years and an interest rate equal to 10 percent with all remaining cost data and cost coefficients unchanged, then the contribution of capital investment to the total annual cost will be significantly reduced. Consequently, energy savings become more important than capital reduction.

Table 5.3: The match matrix for the root node (new cost laws)

	h1	h2	h3
c1	16167	23056	45746
c2	13284	12908	59706
c3	19550	71198	72601

The match matrix corresponding to these new cost laws is presented in Table 5.3. The initial design involves matches c1-h3, c2-h2 and c3-h1. The resulting design is illustrated in Figure 5.7. The network features zero utility consumption and the energy cost is removed from the total annual cost. Clearly, capital cost is dominant and further decomposition is unnecessary.

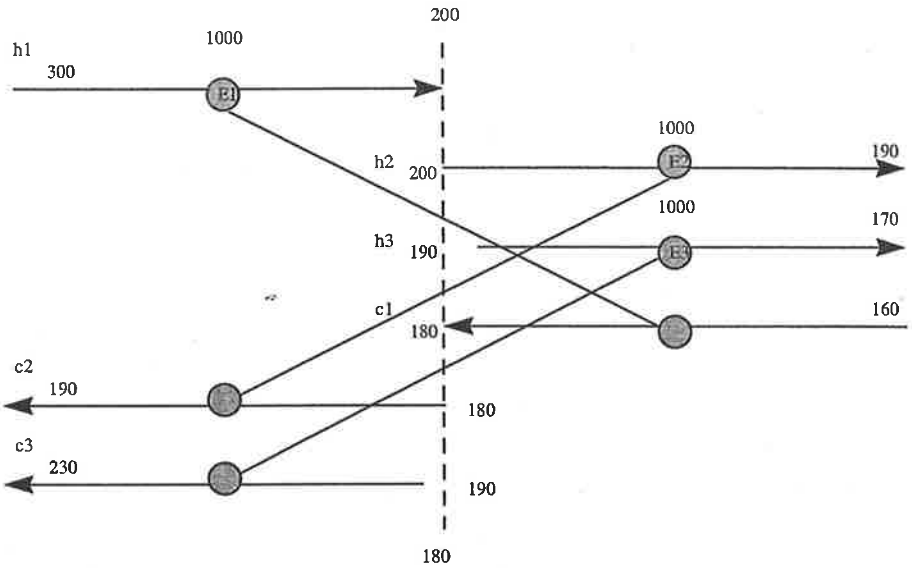


Figure 5.7: Design with new cost laws (plant life: 10 years)

5.5.1.2 Case Study 2

This example was first studied by Rev and Fonyo (1991), and later by Zhu et al. (1995). The stream data are summarised in the Table 5.4. The relevant cost data were applied by Zhu et al. (1995).

Table 5.4: Stream data and relevant costs

Stream	Supply temperature (°C)	Target temperature (°C)	CP (kW/K)	Film transfer coefficient (W/m^2K)	Enthalpy change (kW)
h1	159	77	2.285	100	187.37
h2	267	80	0.204	40	38.148
h3	343	90	0.538	500	136.114
c1	26	127	0.933	10	94.233
c2	118	265	1.961	500	288.267
hot utility	300	300		50	
water	20	40		200	

Capital cost data:

Capital cost: $3800+750*A^{0.83}$

Plant life: 6 years

Interest rate: 10%

Utility cost data:

Cost of hot utility: 110$/kW yr.

Cost of cold utility: 10$/kW yr.

Design for the root node

The match matrix for the root node is presented in the Table 5.5. The initial design involves matching h1-c1 and h3-c2 (Figure 5.8). Hot stream h2 is cooled by cold utility. The total annual cost is $47,770.

The remaining parts of the problem are shown in Figure 5.9. The single cold stream c2 necessitates a sequential matching strategy. The remaining part of hot stream h1 can not match with cold stream c2 due to temperature infeasibility. Following the design rules of the new method, the existing matching pattern of the cold stream c2 (h3-c2) is broken. The cold stream c2 then sequentially matches with hot streams h2 and h3 (Figure 5.10). Following this matching, no further process-process matches are available to reduce the cost. The total annual cost for this design is $47,610.

Table 5.5: The match matrix for the root node

	h1	h2	h3
c1	17805	14969	7355
c2	41634	39190	27628
cold utility	5911	2332	2994

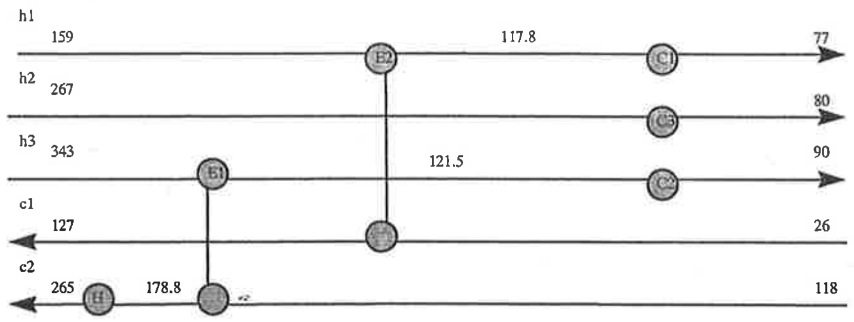


Figure 5.8: The initial design for the root node, the total annual cost: $47,770

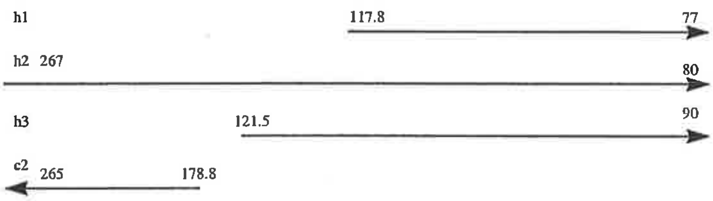


Figure 5.9: The remaining parts for the root node

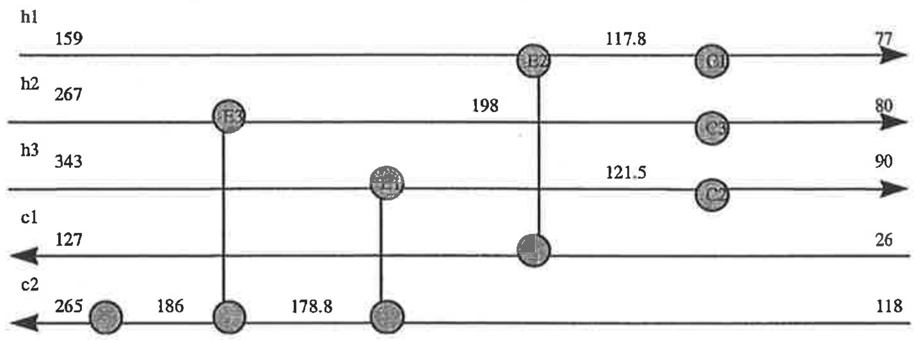


Figure 5.10: Design for the root node, the total annual cost : $47,610

In the design shown in Figure 5.10, the cold stream c2 matches with hot streams h2 and h3. Stream splitting will be considered to potentially improve the driving forces. The design following stream splitting results in a minor reduction in cost (from $47,610 to

$46,310). The fractional contribution of energy cost to the total annual cost d is 0.37. This value is below the suggested constraint of 0.5, indicating that the problem is a capital-cost dominant problem. Further decomposition of the root node is unnecessary.

The initial and optimal designs proposed by Zhu et al.(1995) are illustrated in Figures 5.11 and 5.12. These designs were determined using block decomposition and subsequent mathematical optimisation. The proposed method produces a slightly improved network. However, the most notable feature is the considerable reduction in effort that has been achieved.

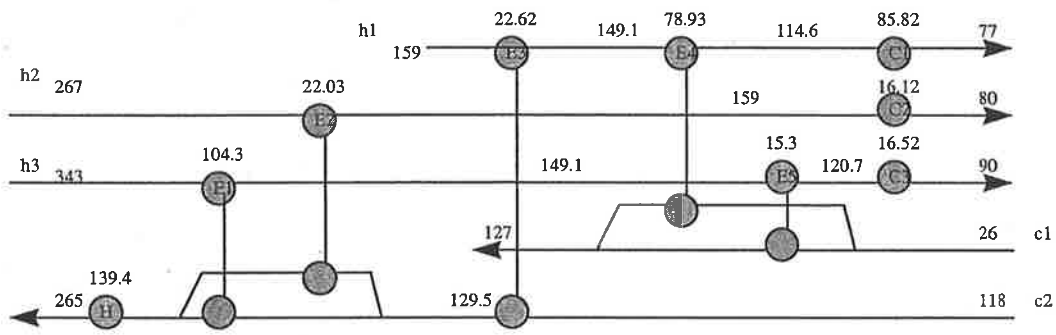


Figure 5.11: The initial design by Zhu et al. (1995), the total annual cost: $51,190

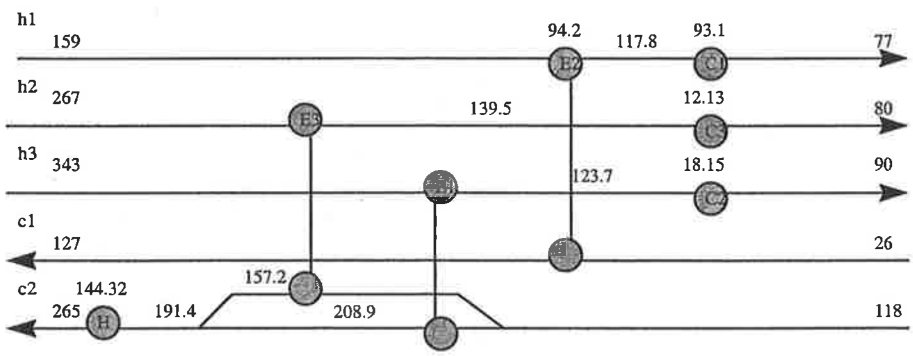


Figure 5.12: Optimal design by Zhu et al, the total annual cost: $46790.

5.5.2 Energy-Cost Dominant Problems

For energy-cost dominant problems, energy cost contributes more than half of the total annual cost. To recover more energy, the root node is decomposed into two child nodes. These child nodes may be decomposed further.

Five case studies including the well-known Aromatics Plant are presented to demonstrate recursive synthesis. For all case studies, the recursive synthesis method achieves a result better (or at least identical to) than the best designs proposed by other researchers. Usually, the recursive synthesis method requires a significantly reduced effort compared to current methods such as the Pinch Design Method.

5.5.2.1 Case Study 3

This problem was studied by Linnhoff et al. (1990) and Zhu et al. (1995). The stream data and relevant cost data are presented in Table 5.6.

Table 5.6: Stream and cost data for case study 3

Stream	h1	h2	hot utility	c1	c2	cold utility
Tin (°C)	150	170	180	50	80	20
Tout (°C)	50	40	180	120	110	40
CP(kW/K)	200	100		300	500	

U: 100 Wm^2/K

Exchanger cost: ($) $30800+750A^{0.81}$

Plant life time: 6 years

Rate of interest: 10%

Hot utility cost: 110 $/kW yr.

Cold utility cost: 10 $/kW yr.

Design for the root node

The match matrix for the root node is presented in Table 5.7. It produces an initial design for the root node involving matches h1-c1 and h2-c2 (Figure 5.13). Further matching is not possible for the remaining part of the design. Utility cost for the design is $990,000. This presents approximately 60 percent of the total annual cost $1,648,394. Clearly, the root node is an energy-cost dominant problem.

Table 5.7: The match matrix for the root node

	h1	h2
c1	640071	1326575
c2	635947	1008323

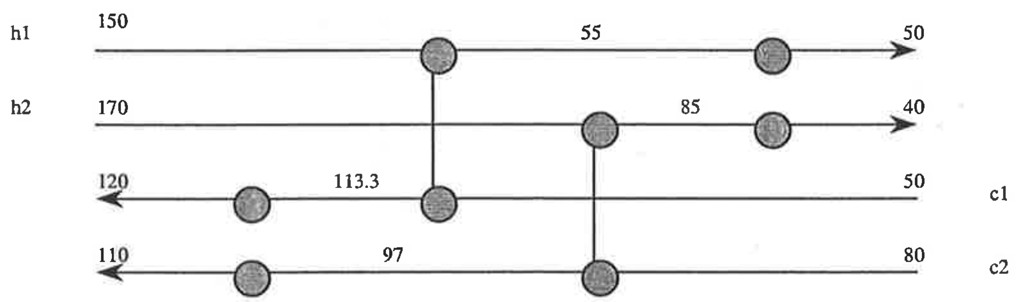


Figure 5.13: Design for the root node

Design of the level-two nodes

Since the root node is an energy-cost dominant problem, further decomposition for the root node is required. The Supertarget algorithm was invoked to determine an optimal HRAT prior to detailed design. The results are presented in Table 5.8.

Table 5.8: Supertarget results for case study 3

No of streams	$HRAT_{opt}$ (K)	Pinch for hot (°C)	Pinch for cold (°C)	d
7	8.9	88.9	80	0.54

The system is decomposed at temperatures 88.9 (°C) for hot streams and 80 (°C) for cold streams with the value of HRAT = 8.9 K.

The match matrix for node 1 is presented in Table 5.9. Its initial design involves matching h1-c2 and h2-c1. No further match is available for the remaining part of the problem. The initial design is the final design for node 1 (Figure 5.14). Utility cost is \$733,700 roughly about 66 percent of the total annual cost of \$1,107,070. However, the design requires only hot utility and further decomposition is unnecessary.

By contrast, node 2 has single cold stream c1, the problem requires a sequential matching strategy. Cold stream c1 is finally split to match with the hot streams (Figure 5.14). For the resulting network, utility cost contributes about 7.5 percent to the total annual cost and further decomposition is unnecessary for node 2. The two level-two designs may now be merged.

The result of this process is shown in Figure 5.14. The total annual cost is \$1,594,370 with a hot utility consumption of 6,670 kW and a total area are of 21,200 m^2.

Table 5.9: The match matrix for the node 1

	h1	h2
c1	245502	583012
c2	524058	916416

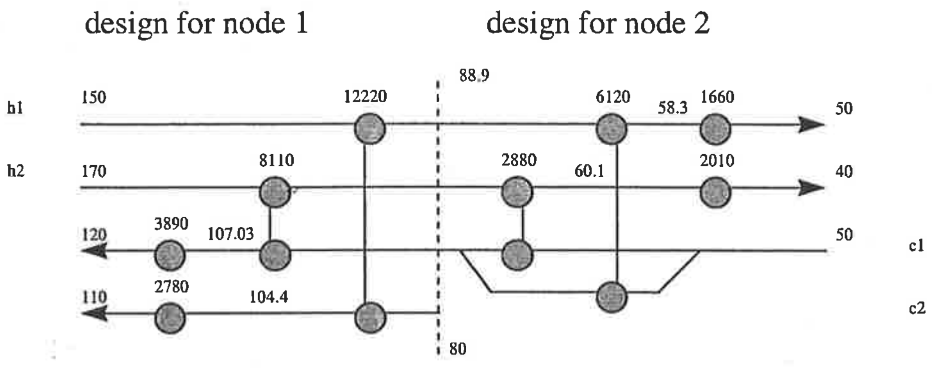


Figure 5.14: Pre-optimal design, the total annual cost:$1,594,370

As a final step in the design, the constraint on the partition temperature is relaxed for the hot streams h1, h2 and cold stream c1. The design following this trade-off is illustrated in Figure 5.15. The total annual cost for the design is reduced slightly to $1,593,100. Note that this design is identical to the optimised design 1 proposed by Zhu et al. (1995).

Again a substantial reduction in overall design effort has been achieved.

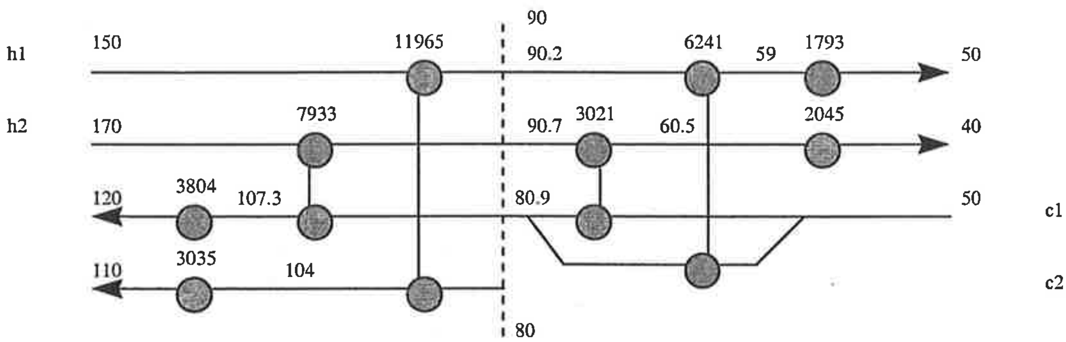


Figure 5.15: Design achieves the total annual cost $1,593,100

5.5.2.2 Case Study 4

This simple example was studied by Linnhoff et al. (1982), Yee and Grossmann (1990), Ciric and Floudas (1990) and Zhu et al. (1995). The stream data and relevant cost data are summarised in Table 5.10.

Table 5.10: Stream and cost data

Stream	h1	h2	stream	c1	c2	water
Tin(°C)	443	423	450	293	353	293
Tout(°C)	333	303	450	408	413	313
Cp(kW/K)	30	15		20	40	

U= 800 (Wm^2/K) for all matches without involving hot utility (steam)

U=1200 (Wm^2/K) for matches involving hot utility (steam).

Annual exchanger cost: ($) $1000A^{0.6}$ for exchangers, coolers.

Annual exchanger cost: ($) $1200A^{0.6}$ for heaters

Hot utility cost: 80 $/kW yr.

Cold utility cost: 20 $/kW yr.

Design for the root node

The match matrix for the root node is presented in Table 5.11. It produces an initial design involving matches h1-c2 and h2-c1 (Figure 5.16). Further savings cannot be achieved after considering the remaining part. The design costs $106,640. Annual hot and cold utility consumptions are 500 kW and 900 kW respectively.

Utility cost ($58,000) contributes 54 percent of the total annual cost for the root-node design. This value indicates that this case is an energy-cost dominant problem and further decomposition is required.

Table 5.11: The match matrix for the root node

	h1	h2
c1	38349	60334
c2	46303	158477

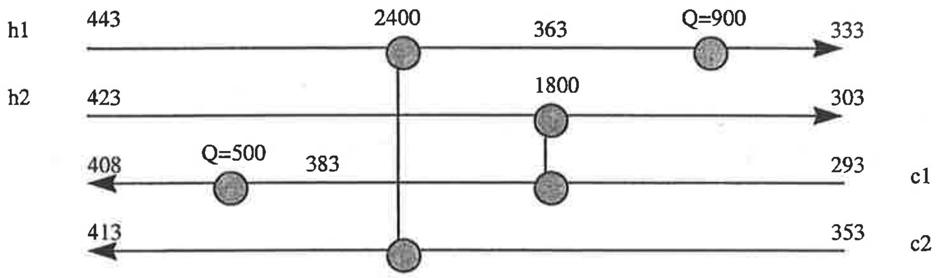


Figure 5.16: The design for the root node, the total annual cost: $106,638

Design of the level-two nodes

The system is decomposed into two child nodes (above and below the pinch) using a value of HRAT = 5.6 K, as determined using the Supertarget algorithm.

Table 5.12: The match matrix for node 1

	h1	h2
c1	155686	28783
c2	30559	134529

The match matrix for node 1 (above pinch) is presented in Table 5.12. It produces an initial design with matches h1-c2 and h2-c1 (Figure 5.17). The remaining part of the design contains single hot stream h1 and single cold stream c1 producing a single match h1-c1 (Figure 5.18). It is possible to improve the driving forces by splitting both h1 and c1, but the calculation shows that this option does not reduce the cost.

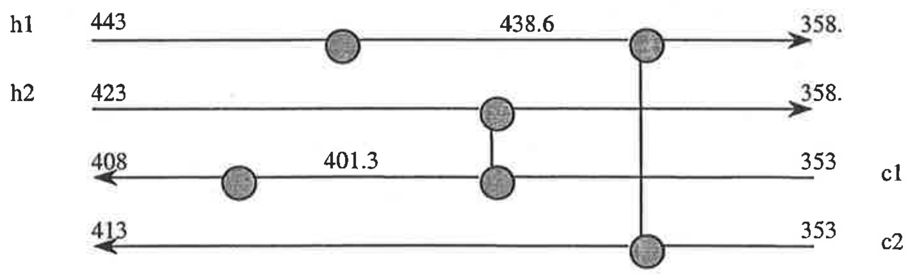


Figure 5.17: The initial design for node 1

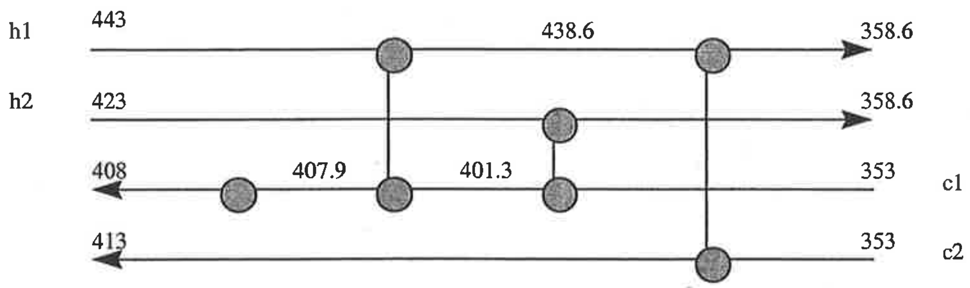


Figure 5.18: The design for node 1

Node 2 (below the pinch) consists of a single cold and two hot streams. Hence, the cold stream is split to match with the two hot streams. The resulting design is combined with that for node 1 (Figure 5.19).

The partition temperatures and splitting ratio for c1 are then optimised. The cost is reduced to $80,130. The small heater is removed during this process (Figure 5.20).

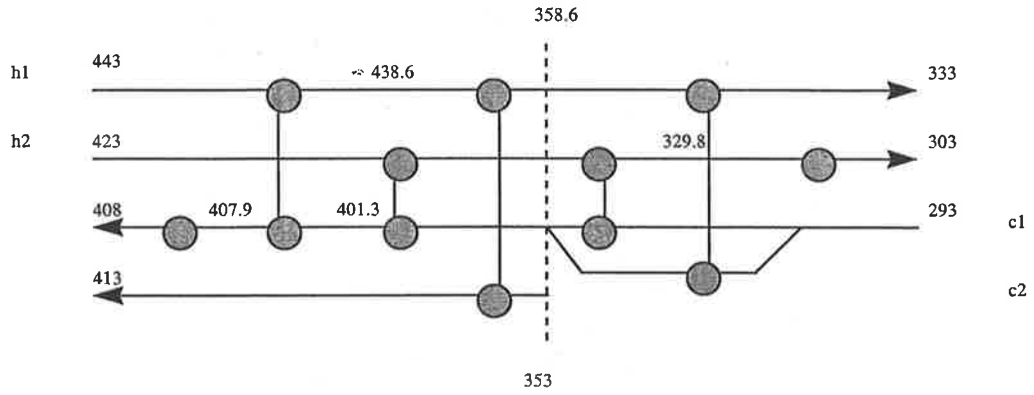


Figure 5.19: Combination of the two design for node 1 and node 2, $80,900

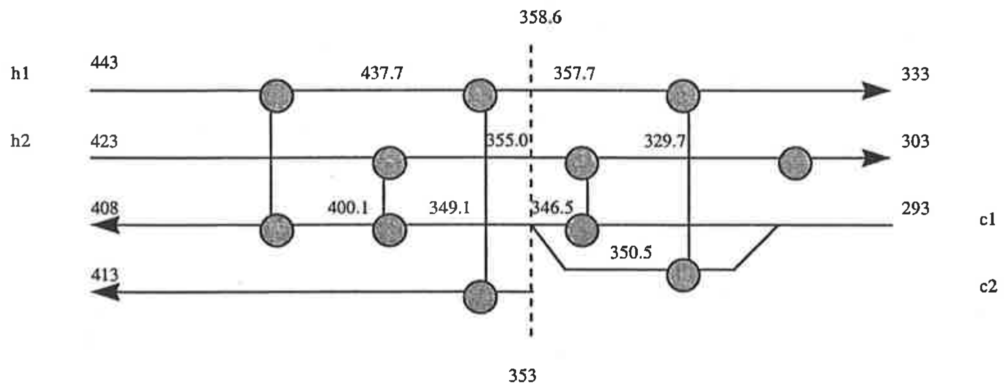
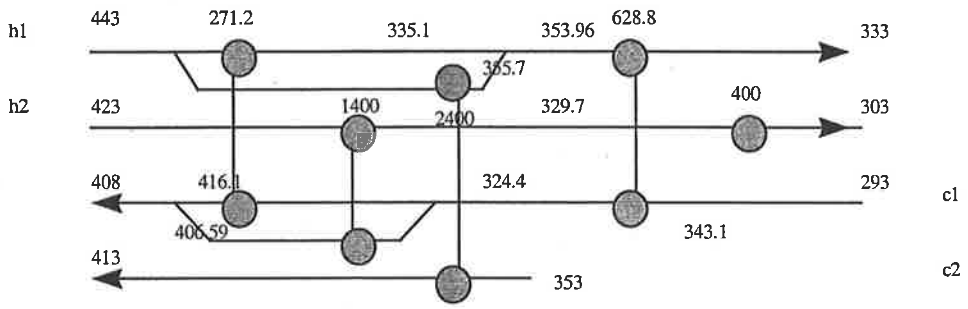


Figure 5.20: The optimal design, $80130

Yee and Grossmann (1990) discovered the solution shown in Figure 5.21 using a two-stage superstructure. Their MINLP formulation involves 62 constraints and 50 variables. Nine of variables are binary. The solution obtained by Linnhoff et al. (1982) is shown in Figure 5.22. It achieves an annual cost of $89,830. Figure 5.23 illustrates the design proposed by Zhu et al. (1995). This design is obtained by optimising the heat loads of their initial design. The design was further optimised to yield a final design which is identical to that proposed by Yee and Grossmann. The design resulting from this recursive algorithm achieves a slightly improved solution with significantly reduced effort.



The total annual cost: $80,274

Figure 5.21: Optimal design by Yee and Grossmann (1990)

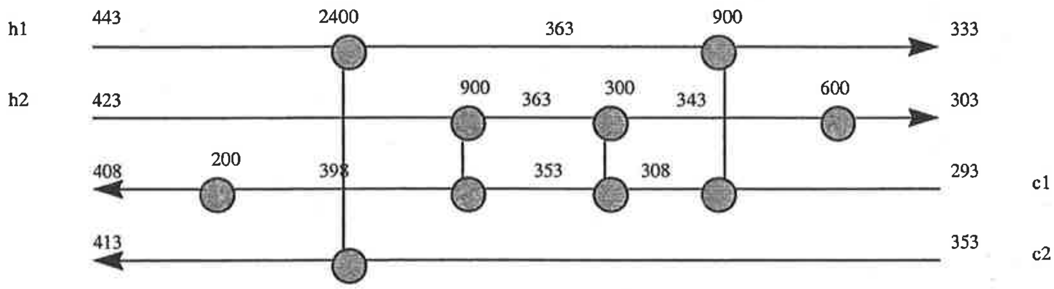


Figure 5.22: Design from Linnhoff et al. (1982)

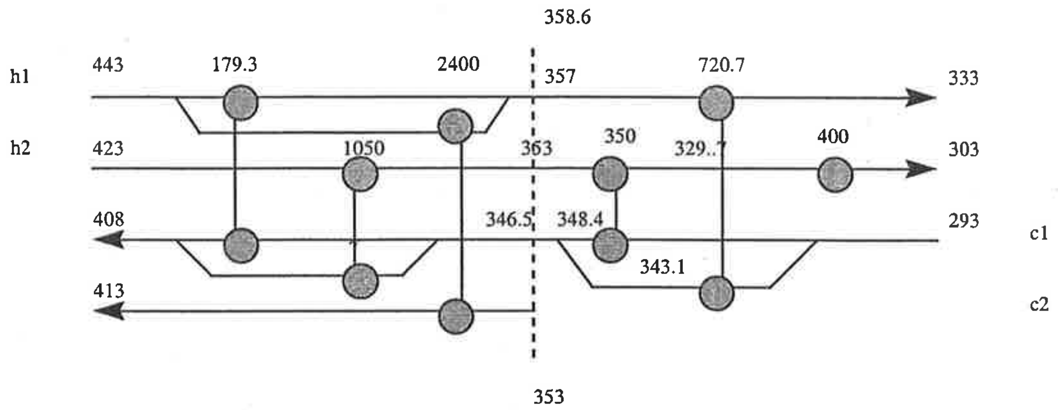


Figure 5.23: Optimal design by NLP3 model (Zhu et. al. 1995) $81,769

Table 5.13: Stream data for case study 5

	T(°C) Supply	T(°C) Target	CP (kW/K)	h (W/m^2K)	Q (kW)
h1	120	65	25	500	1375
h2	80	50	150	250	4500
h3	135	110	145	300	3625
h4	220	95	10	180	1250
h5	135	105	130	250	3900
c1	65	90	75	270	1875
c2	75	200	70	250	8750
c3	30	210	50	150	9000
c4	60	140	25	450	2000
steam	250	249		350	
water	15	16		200	

Cost for heat exchanger: ($) $30800+750A^{0.81}$

Plant life: 6 years

Interest rate: 10% per annum

Cost for hot utility: 110 ($kW/yr.)

Cost for cold utility: 10 ($kW/yr.)

5.5.2.3 Case Study 5

Case 5 was proposed by Ahmad and Linnhoff in 1990 to demonstrate the reliability of an appropriately linearised cost law for targeting and design. The relevant stream and utility data are summarized in Table 5.13.

Design for the root node

The match matrix is presented in Table 5.14. The resulting initial design involves matches h1-c1, h3-c2, h4-c4 and h5-c3 (Figure 5.24). Further matching is not possible for the remaining part of the design. The root node design is shown in Figure 5.24 incurring a total cost of $1,632,380.

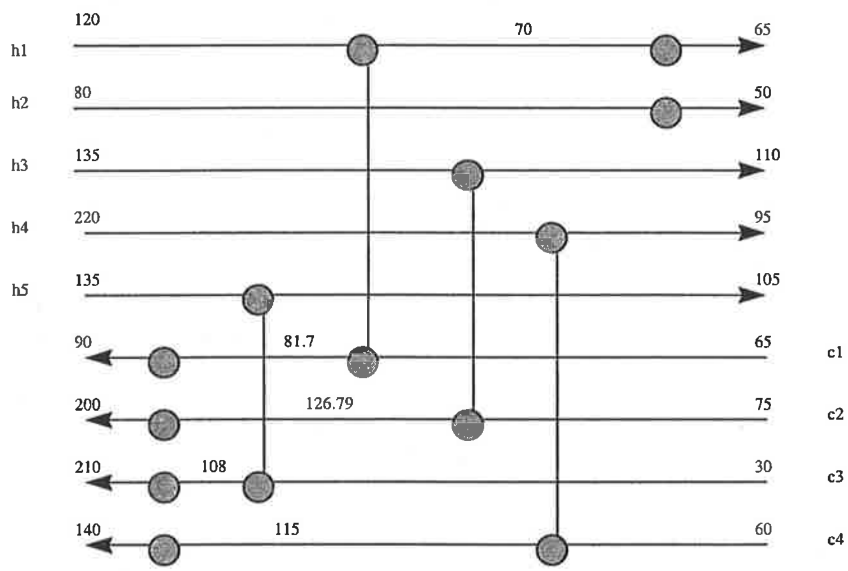


Figure 5.24: The initial design for case study 5, total annual cost = $1,632,380

The utility cost in the design for the root node is $1,322,250. This constitutes about 80 percent of the total annual cost. Clearly, the problem is an energy-cost dominant and decomposition of the root node is necessary.

Table 5.14: The match matrix

	h1	h2	h3	h4	h5
c1	167313	258705	56909	95913	63273
c2	993462	1126320	663732	880677	663523
c3	905107	912685	671240	913182	648031
c4	137624	297030	98986	109291	107191
water	29730	92428	60019	26728	65327

Design of the level-two nodes

The optimal value of HRAT was found to be10 K with a pinch at 80 °C / 70 °C. The root node was divided into two child nodes above and below the pinch.

Table 5.15: The match matrix for node 1

	h1	h3	h4	h5
c1	87533	59865	54268	66064
c2	918842	663732	880677	663523
c3	732764	569399	694120	580222
c4	122458	104554	82736	112040

The match matrix for node 1 (above pinch) is presented in Table 5.15. Solution of assignment problem yields an initial design with matches c1-h1, c2-h5, c3-h3 and c4-h4 as shown in Figure 5.25.

The match matrix for the remaining parts of the design produces subsequent matching of h3-c1 and h5-c4. The network is then evolved to the design in Figure 5.26. The remaining part of this design involves h3, c2, c3 and c4. So, we have a sequential match problem or a stream splitting problem. This simple problem can be easily designed and the final design is shown in Figure 5.27. The total annual cost is $1,370,780 with $1,014,750 being utility cost.

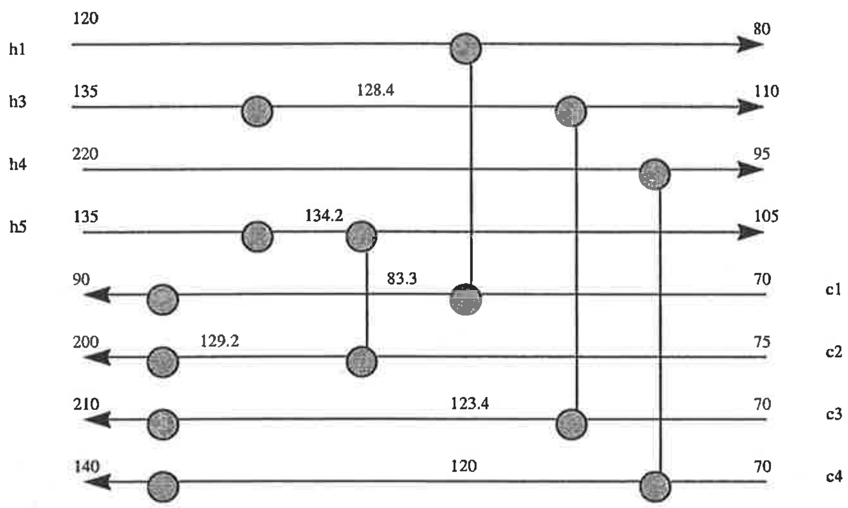


Figure 5.25: The initial design for node 1, the total annual cost $1,411,520.

The match matrix for node 2 is presented in Table 5.16. Solution of match-assignment model identifies matches h1-c4 and h2-c3. Cold stream c1 is heated by hot utility. This initial design costs $189,070. The remaining part of the design involves h2 and c1.

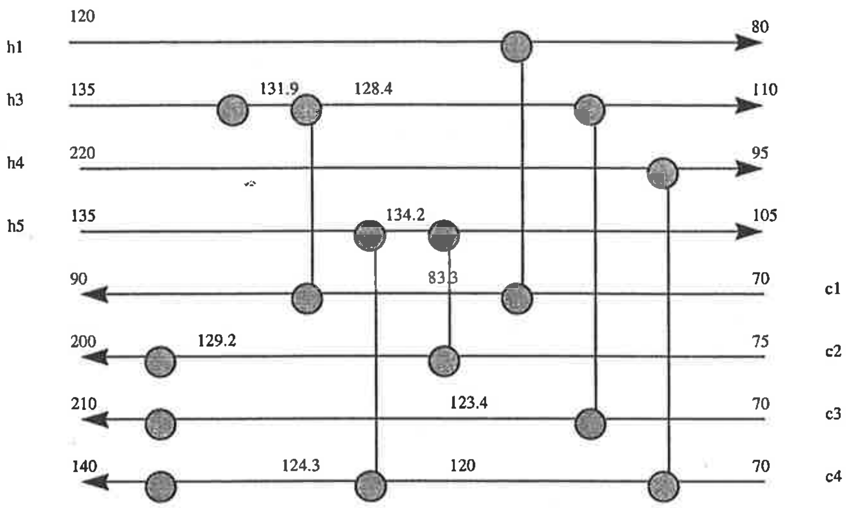


Figure 5.26: Evolution of the initial design.

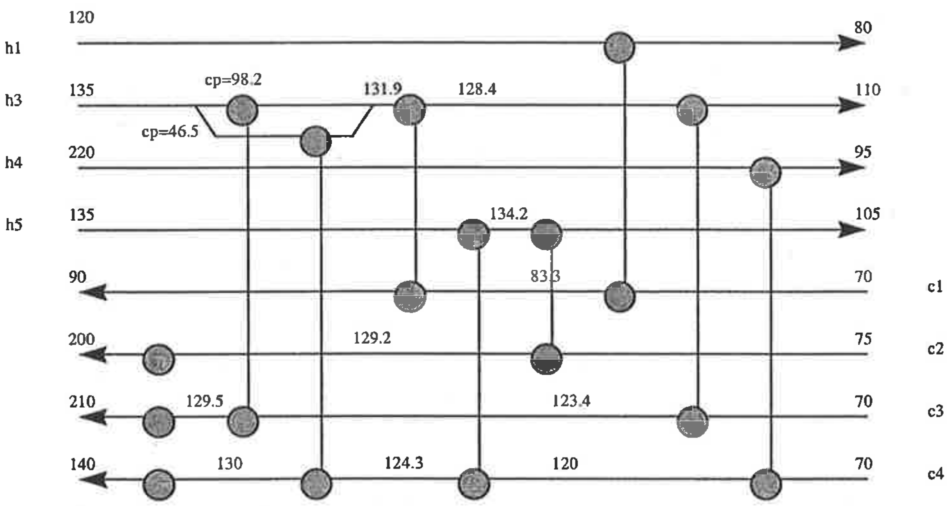


Figure 5.27: The design for node 1.

Splitting h2 to match with streams c1 and c2 produces a design with total annual cost $163,610 (Figure 5.28).

Table 5.16: The match matrix for node 2

	h1	h2	steam
c1	51417	109137	49759
c3	205080	114737	234004
c4	24589	103563	35393

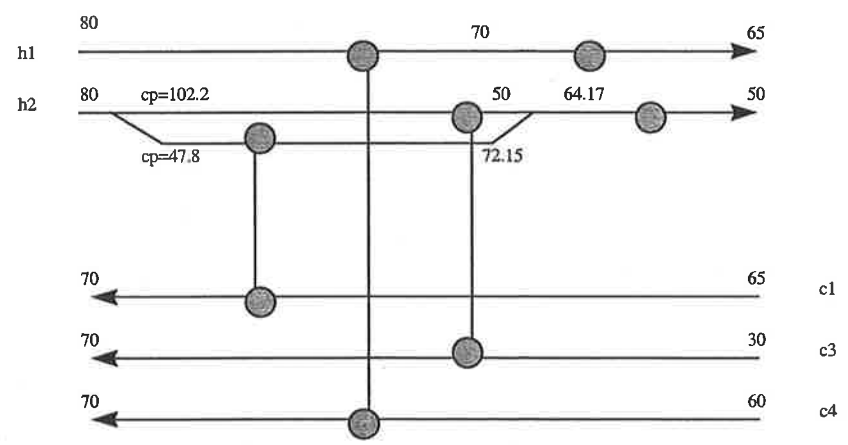


Figure 5.28: The design for node 2, total annual cost $ 163,610

Design for the level-three nodes

The designs for node 1 and node 2 both are threshold designs. Normally, further decomposition is unnecessary. However, in the node 1 design, the driving forces on several units are very close to 5 K. These driving forces may be improved by further decomposition of node 1.

To minimise the total number of the streams in the level-three, node 1 is divided into two children node 1-1 and node 1-2 using a partition temperature of 135 °C for the hot streams and 125 °C for the cold streams.

The node 1-1 contains one hot stream and three cold streams. The design resulting is shown in Figure 5.29.

The design for node 1-2 starts on the right side of the system. The system's match matrix is presented in Table 5.17 and matches h1-c1, h3-c3, h4-c4 and h5-c2 are identified as optimal (Figure 5.30). The resulting design costs $427,740.

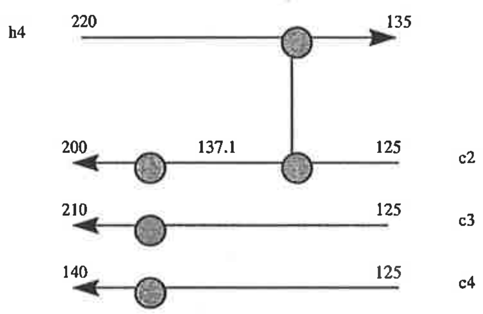


Figure 5.29: The design for node 1-1.

The remaining part of the design involves hot streams h3, h5, cold stream c1, c3 and c4. The design for the remaining part involves matches h3-c4 and h5-c1 (Figure 5.31). The final design for node 1-2 achieves a total annual cost of $270,320.

Table 5.17: The match matrix for node 1-2

	h1	h3	h4	h5
c1	87533	64907	145552	73874
c2	320635	75089	372729	95490
c3	240256	113858	291398	153042
c4	79945	116855	130859	140106

The combination of the two designs for node 1-1 and node 1-2 is shown in Figure 5.32. The heaters on both node 1-1 and node 1-2 are merged to left side of the network. It produces a design with the total annual cost $1,332,580. Two variables, which are underscored, need to be optimized. The subsequent optimization produces the design shown in Figure 5.33 with the total annual cost reduced to $1,321,500.

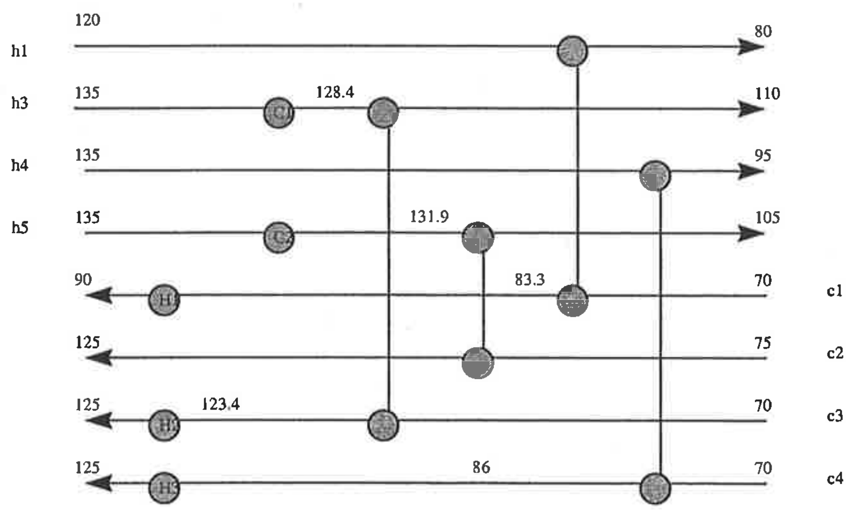


Figure 5.30: The initial design for node 1-2.

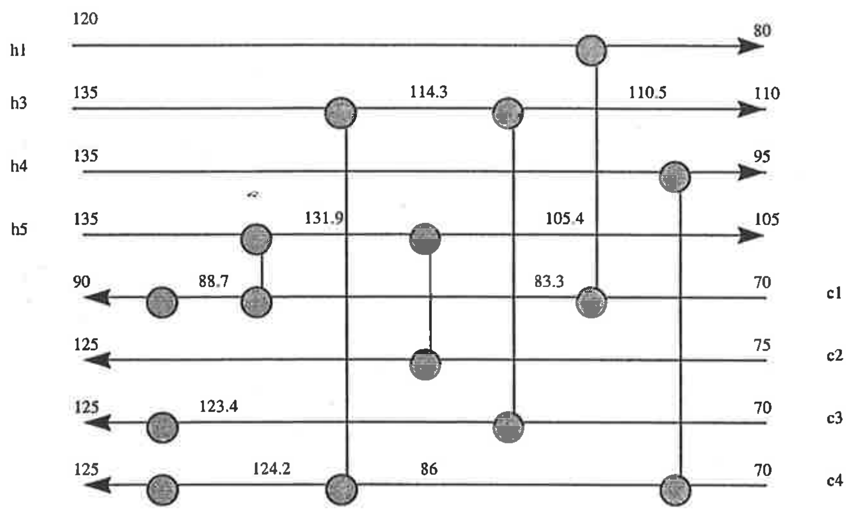


Figure 5.31: The design for node 1-2

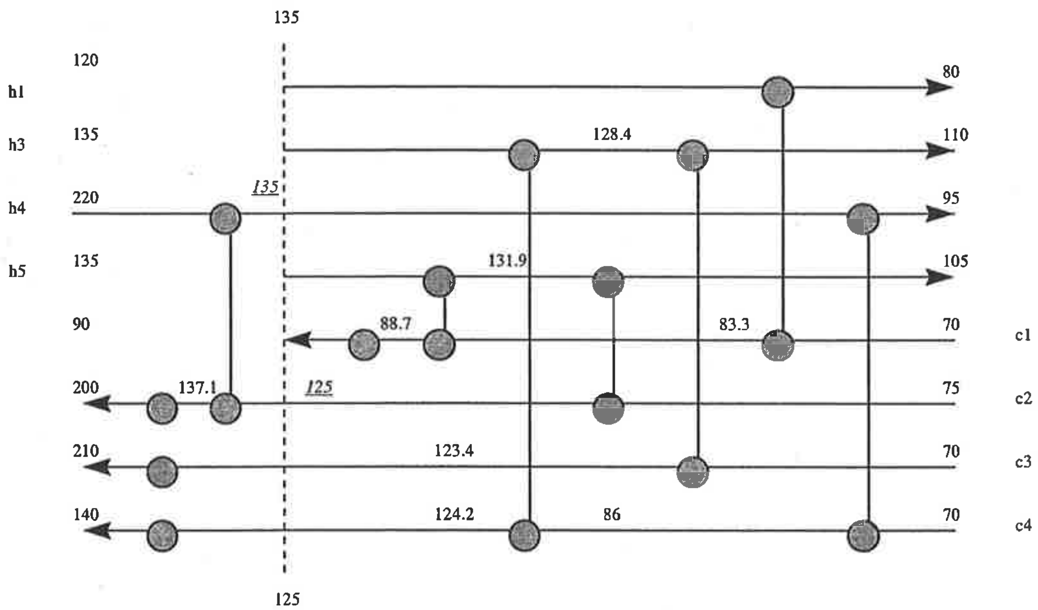


Figure 5.32: Combination of the two designs for node 1.

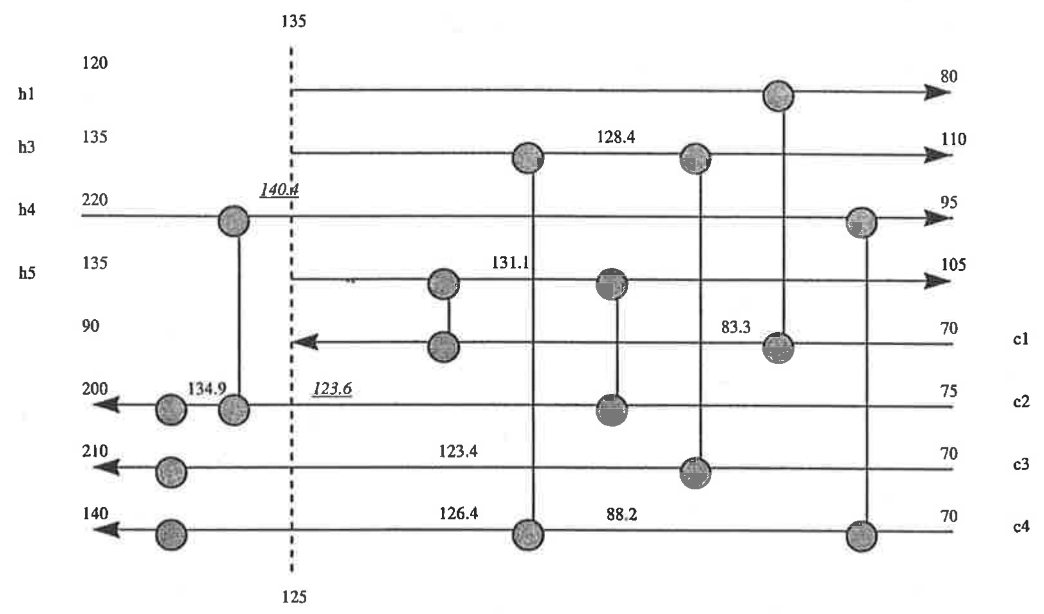


Figure 5.33: The optimal design for node 1

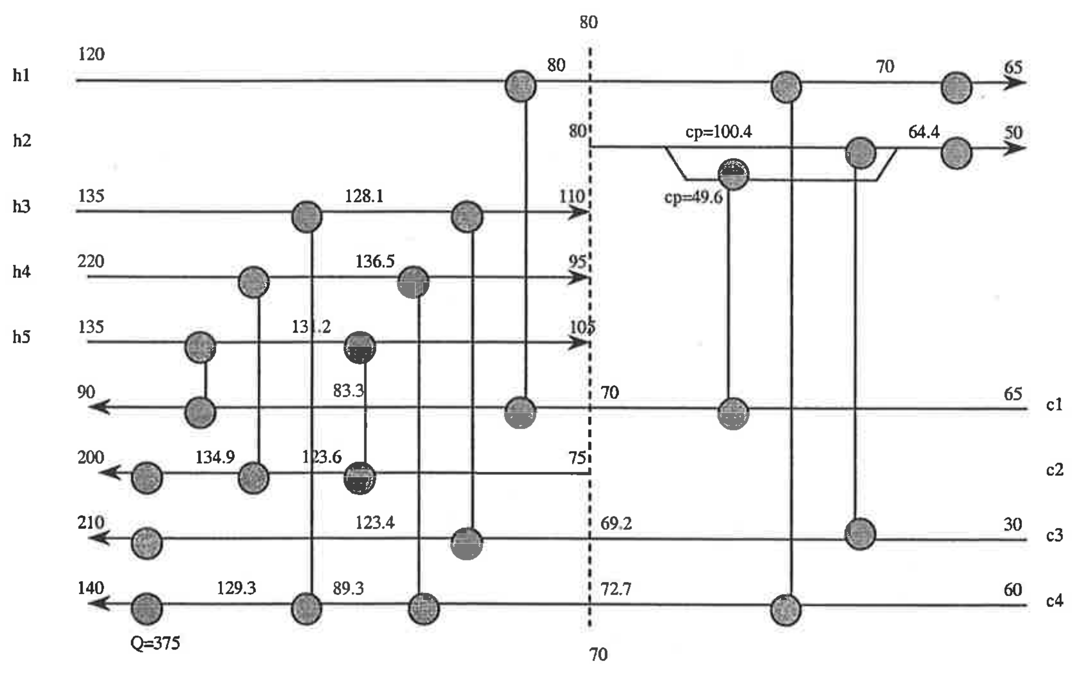
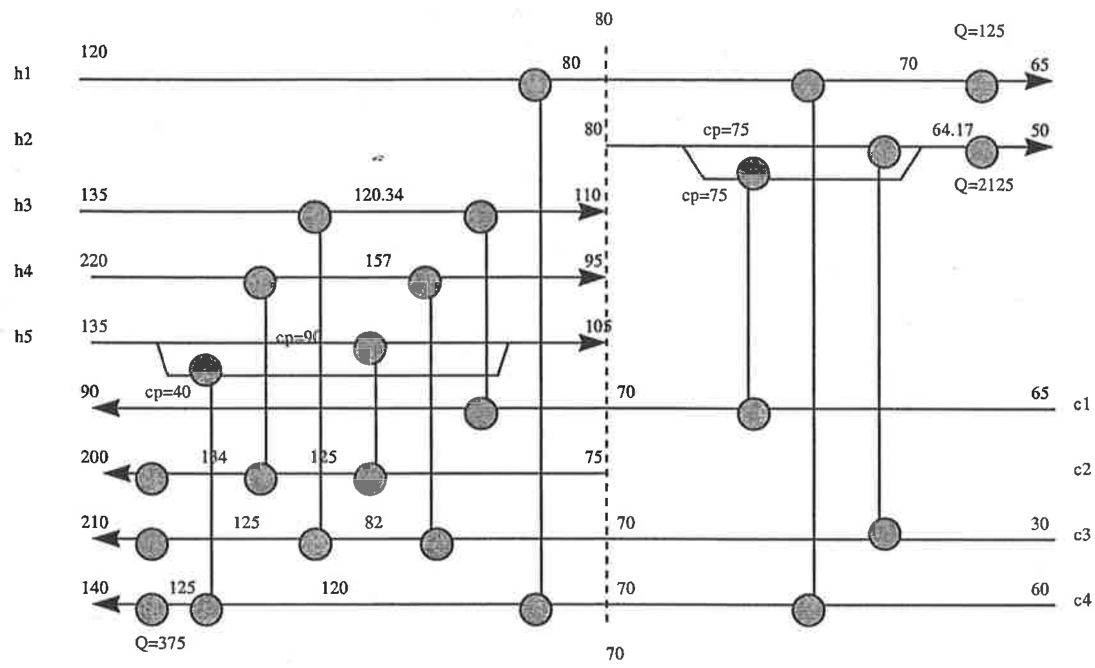


Figure 5.34: The optimal design for three level decomposition.



The total annual cost is $ 1,513,510

Figure 5.35: Design for case study 5 by Ahmad et al. (1990)

The design for node 2 is shown in Figure 5.28 and further decomposition is unnecessary. The two designs for node 1 and node 2 are combined. The optimisation of the partition temperatures produces a final design with the total annual cost $1,481,670 (Figure 5.34).

Compared to the design by Ahmad et. al. (1990) (Figure 5.35), the design produced by the new method involves an identical number of heat exchangers at a reduced total annual cost. The stream split has also been avoided.

5.5.2.4 Case Study 6: The Aromatics Plant

This problem is a widely studied industrial sized problem (Linnhoff and Ahmad, 1989, Polley and Shahi, 1991, Suaysompol and Wood, 1991, Zhu et. al., 1995). It is based on a simplified flowsheet for one of the largest aromatic complexes in Europe. The reaction section is not available for heat integration due to the constraints imposed by start-up and safety (Linnhoff et al., 1982, Ahmad and Linnhoff, 1989). The stream data and relevant cost data are summarised in Table 5.18.

Table 5.18: Stream and cost data for case study 6

Stream	supply temperature (°C)	target temperature (°C)	CP (kW/K)	h (W/m^2K)	enthalpy change (kW)
h1	327	40	100	500	28700
h2	220	160	160	500	9600
h3	220	60	60	500	9600
h4	160	60	400	500	46000
c1	100	300	100	500	20000
c2	35	164	70	500	9030
c3	85	138	350	500	18550
c4	60	170	60	500	6600
c5	140	300	200	500	32000
hot oil	330	320		500	
water	15	25		500	

Exchanger cost($) = $700A^{0.83}$

Plant life : 5 years

Interest rate:5%

Cost of oil; $ 68.5 /kW yr.

Cost of water: $ 9.13/ kW yr.

Design for the root node

The match matrix for the root node is presented in the Table 5.19. A single hot utility is required to balance the matrix. An initial design produced by solving the match selection model involves matches h1-c1, h2-c5, h3-c2, and h4-c3. Cold stream c4 is not selected for process-process matches and is heated by hot utility.

Two feasible matches exist in the remaining part of the initial design. The match between hot stream h1 and cold stream c4 is chosen by applying an identical match selection procedure. After this design, no further match is available for the remaining part. The final design for the root node is illustrated in Figure 5.36. The total annual cost and utility cost are $2,548,530 and $1,983,050 respectively. Since utility cost contributes about 78 percent to the total annual cost, further decomposition is required.

Table 5.19: The match matrix for the root node

	c1	c2	c3	c4	c5
h1	236145	238205	164879	259261	1229967
h2	795035	30733	649488	53459	1666131
h3	1036377	51341	821553	69253	2056843
h4	1484809	461589	381054	498946	2544545
hot utility	1413004	629654	1291428	461143	2262774

Design for the two level nodes

The optimal HRAT is determined to equal19 K. This value produces a pinch at 160 °C for hot streams and 141 °C for cold streams. The root node is then divided into two child nodes above and below the pinch. These sub-systems nodes are designed separately.

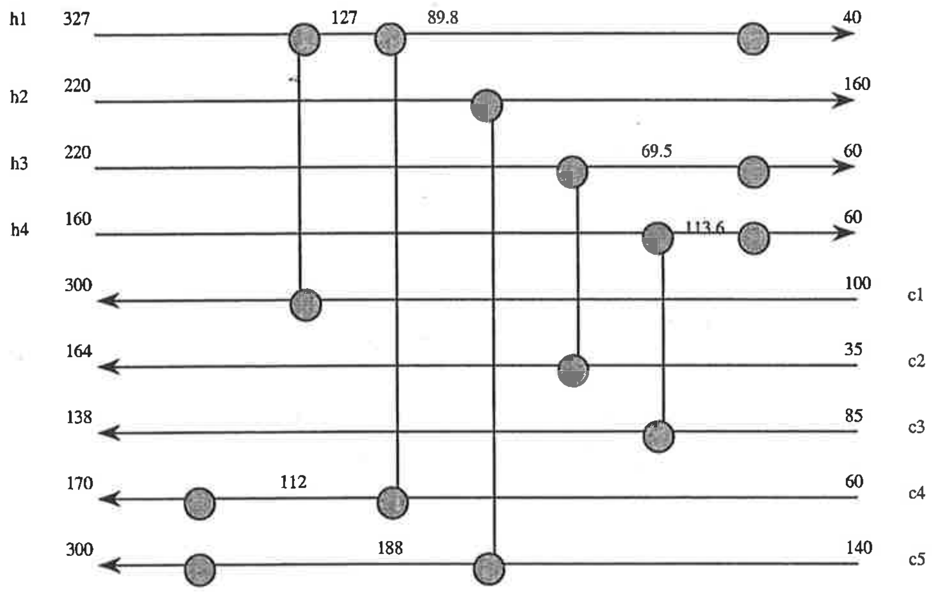


Figure 5.36: Design for the root node

The matches in node 1 start from the partition point (see the match pattern for single match in Figure 4.7 a) and heaters and coolers are placed on the left side of system. The match matrix produced by this match pattern is shown in Table 5.20. An initial design with matches h1-c1, h2-c5 and h3-c4 is identified with cold stream c2 heated to its target temperature by hot utility. The initial design for node 1 is shown in Figure 5.37.

The match matrix for the remaining part of node 1 is shown in Table 5.21. Additional matching of h1-c5 and h3-c2 is identified. No further matches can be found. The resulting design for node 1 is shown in Figure 5.38. The utility cost for the design is \$1,468,410. It contributes more than 80 percent to the total annual cost \$1,770,520.

Table 5.20: The match matrix for node 1

	c1	c2	c4	c5
h1	145088	186802	192177	1150648
h2	1000987	118695	143328	1654614
h3	906198	41535	42956	2022554
hot utility	1128874	113535	122709	2248916

Table 5.21: The match matrix for the remaining part

	h1	h3
c2	59159	12083
c5	1528976	1603106

Matches in node 2 start from the partition point with the heaters and coolers placed on the right side of system. The match matrix of this problem is presented in Table 5.22. An initial design involving process matches h1-c2, h3-c4 and h4-c3 is identified with cold stream c1 and c5 heated to their target temperatures by hot utility (Figure 5.39).

The remaining part of design only involves cold streams c1 and c5, and parts of the hot streams h1, h3 and h4. The remaining sections of hot streams h1 and h3 are impossible to match with cold streams c1 and c5 (temperature infeasibility), hence a single hot stream h4 is available and the problem becomes a sequential match problem. To increase flexibility, the match between hot stream h4 and cold stream c3 is broken. Cold

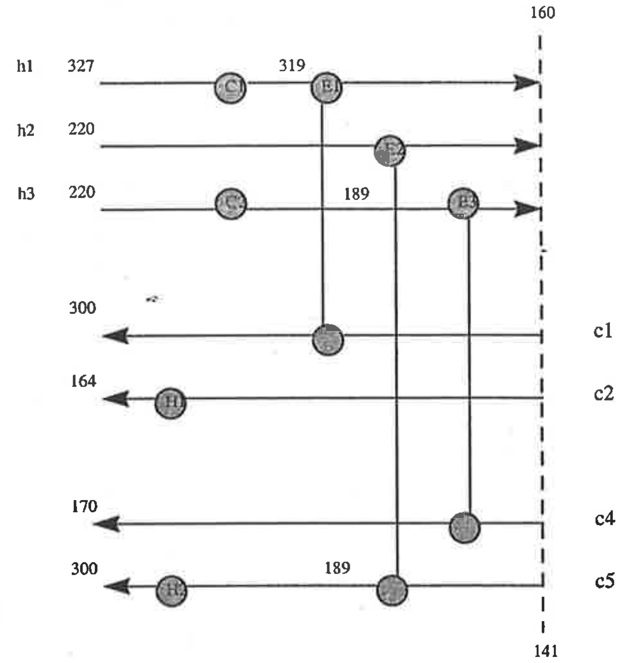


Figure 5.37: The initial design for node 1

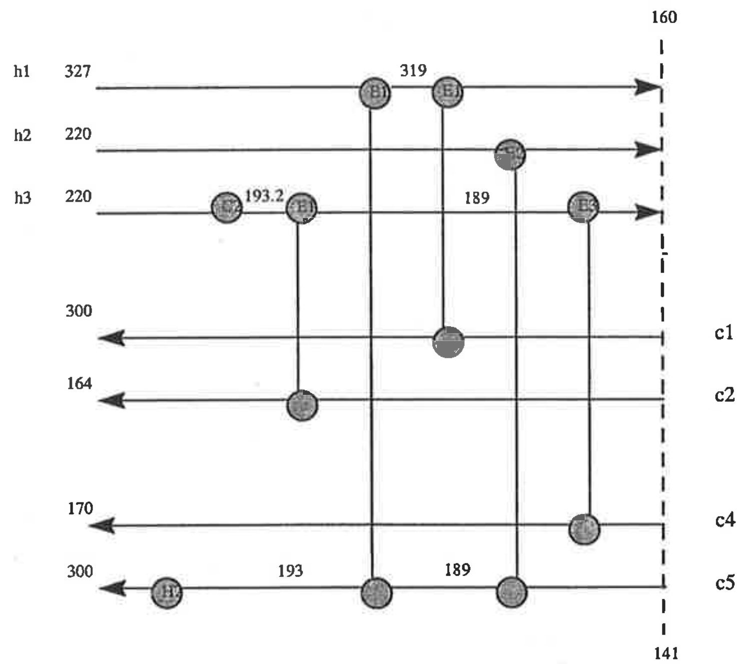


Figure 5.38: Design for node 1

streams c1, c3 and c5 then sequentially match with hot stream h4 in the order of the enthalpy change of the streams. The resulting design for node 2 is shown in Figure 5.40. The energy cost is $208,800 about 34 percent of the total annual cost $621,870.

The combination of the two designs cost $2,392,390. After merging the coolers in hot stream h3 as well as the matches between hot stream h3 and cold stream c4, the cost is reduced to $2,375,200 (Figure 5.41). The total annual cost may be further decreased to $2,333,360 following the optimisation of the partition temperatures (Figure 5.42).

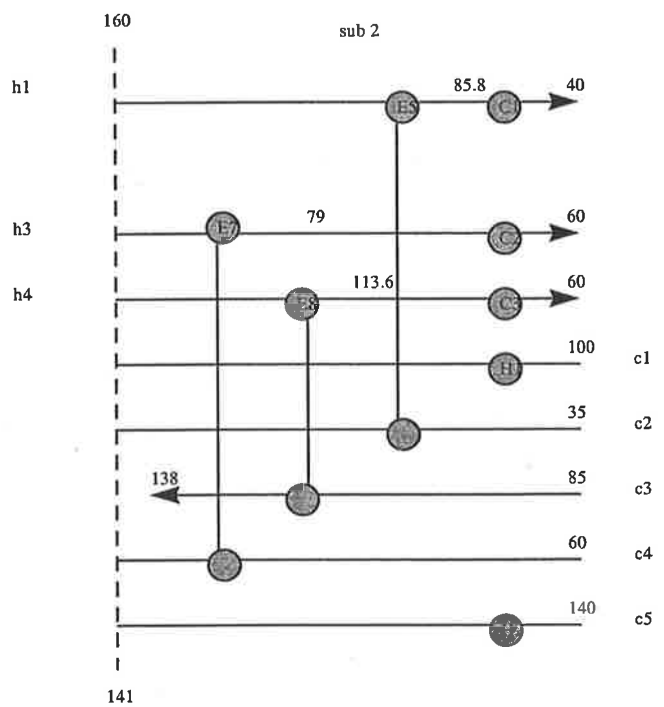


Figure 5.39: The initial design for node 2.

Table 5.22: The match matrix for node 2

	c1	c2	c3	c4	c5
h1	149015	114024	1294221	129133	149742
h3	232184	200861	1292447	68007	74417
h4	438759	407906	381054	427171	453443
hot utility	286987	517243	1291428	339486	14244
hot utility	286987	517243	1291428	339486	14244

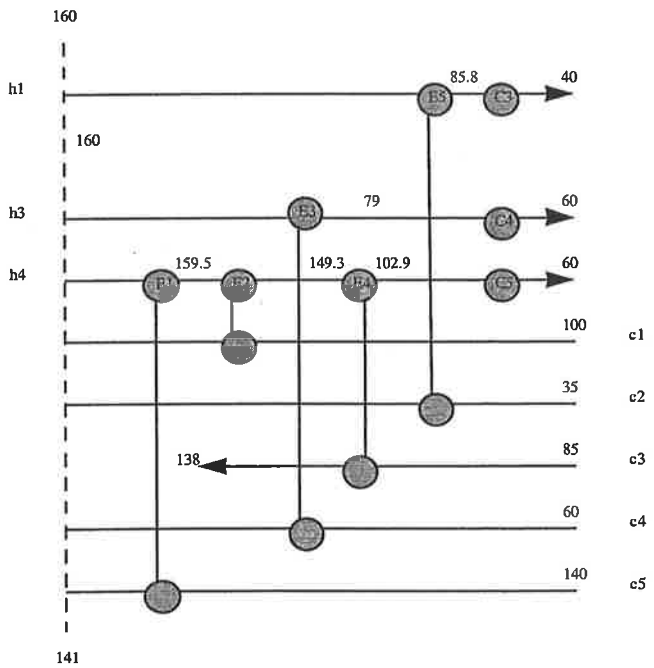


Figure 5.40: The design for node 2

Design for the level-three nodes

Since the node 1 design (Figure 5.38) is an energy-cost dominant problem, further decomposition is required. To minimise the number of the streams on both sides of nodes 1-1 and 1-2, the partition temperatures for node 1-1 and node 1-2 are set at 220 °C and 201 °C for hot streams and cold streams, respectively.

The match matrix for node 1-1 is presented in Table 5.23. It produces a design involving the match h1-c5 for node 1-1(Figure 5.43). The match matrix for node 1-2 is presented in Table 5.24. The initial design contains matches h1-c1, h2-c5 and h3-c4 (Figure 5.43). The remaining parts of node 1-2 involve a single hot stream h3. This problem is a sequential match problem. The match between the hot stream h3 and cold stream c4 is relaxed, then cold streams c2, c4 and part of c5 are sequentially matched with h3 in the order of their target temperatures (Figure 5.44). The heater H3 in the node 1-2 is merged into the heater H2 in node 1-1.

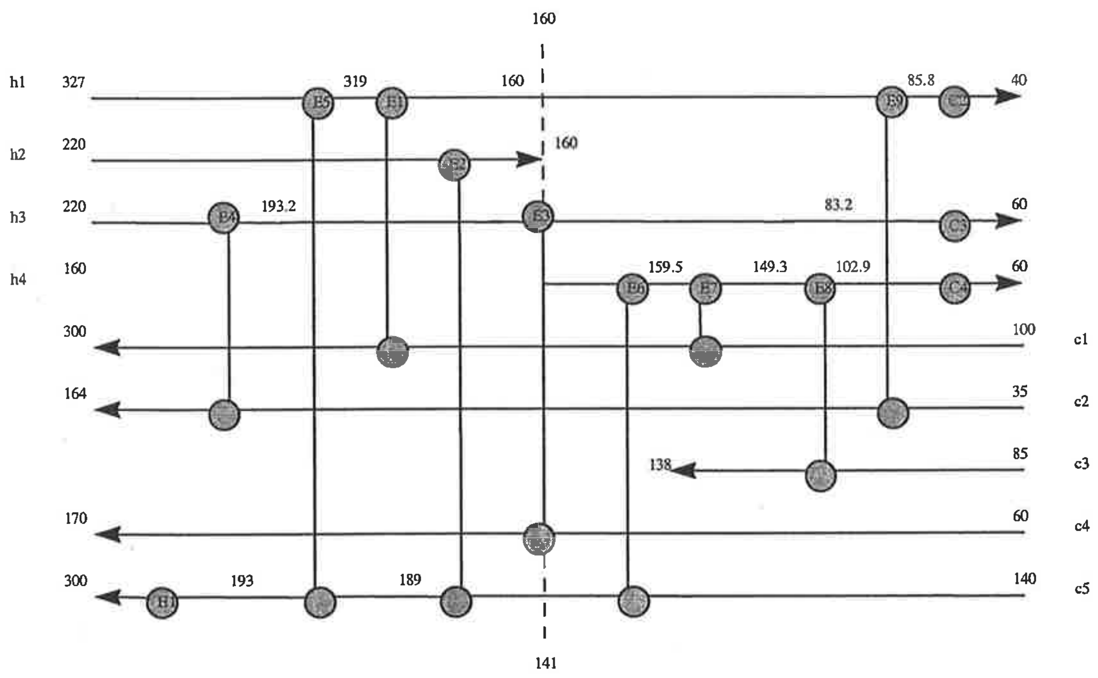


Figure 5.41: Combined design for two level decomposition

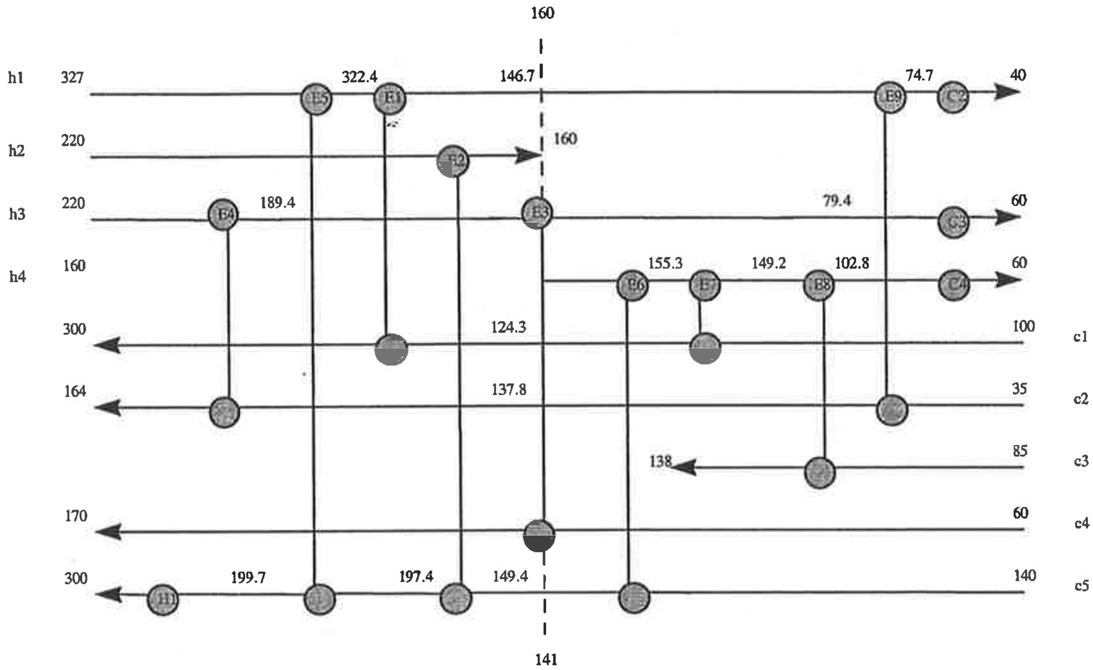


Figure 5.42: Final design for two level decomposition, $2,333,360

Table 5.23: The match matrix for node 1-1

	c1	c5
h1	100439	717401
hot utility	711299	1415229

Table 5.24: The match matrix for node 1-2

	c1	c2	c4	c5
h1	60400	73238	78571	462124
h2	292147	118695	147219	242337
h3	197441	41535	42956	613485
hot utility	422021	113535	122709	841591

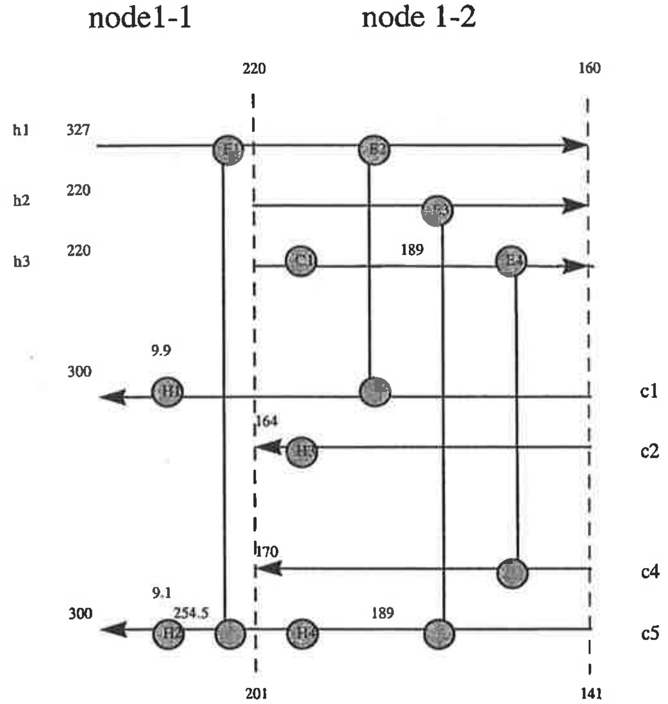


Figure 5.43: The initial design for node 1-1 and node 1-2

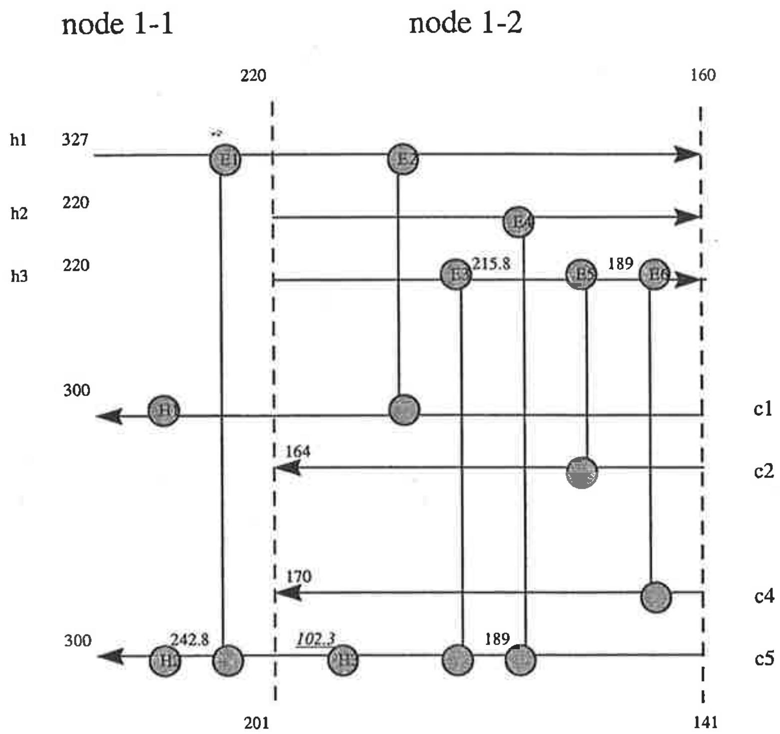


Figure 5.44: Design for node 1-1 and node 1-2

Two partition temperatures in the pre-optimal design of node 1 need to be optimised. Only one of them is a manipulated variable. The optimal design for node 1 is shown in Figure 5.45 and it costs $1,735,010, a lower cost than that of the design presented in Figure 5.38 ($1,770,520).

The design for node 2 shown in Figure 5.40 is dominated by the capital cost and further decomposition is not required.

The combination of two node 1 designs is illustrated in Figure 5.45 with the node 2 designs (shown in Figure 5.40) presented in Figure 5.46. Merging is not required for this pre-optimal design. Seven partition temperatures were optimised and the resulting optimal design costs $2,315,720 (Figure 5.47).

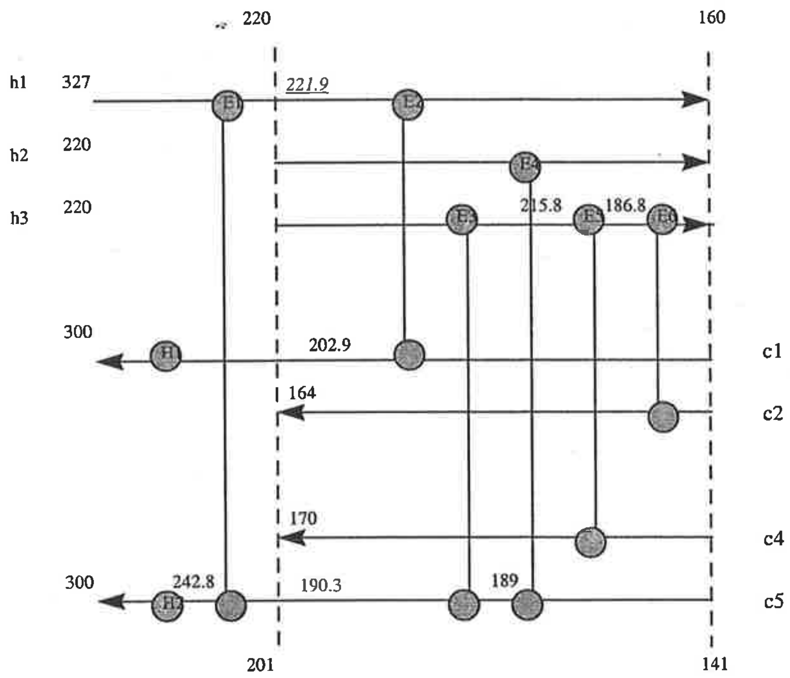


Figure 5.45: Design for Node 1 ($1,735,010)

Although decomposition of node 2 is not required according to the algorithm presented in Figure 5.2, it will be considered to investigate the impact of the further decomposition on the final design.

Node 2 was divided at 119 °C and 100 °C for the hot and cold streams, respectively. The match matrix for node 2-2 is presented in Table 5.25. The initial design involves matches h1-c2, h3-c4 and h4-c3. Additional feasible matches do not exist. The design for node 2-2 is shown in Figure 5.48.

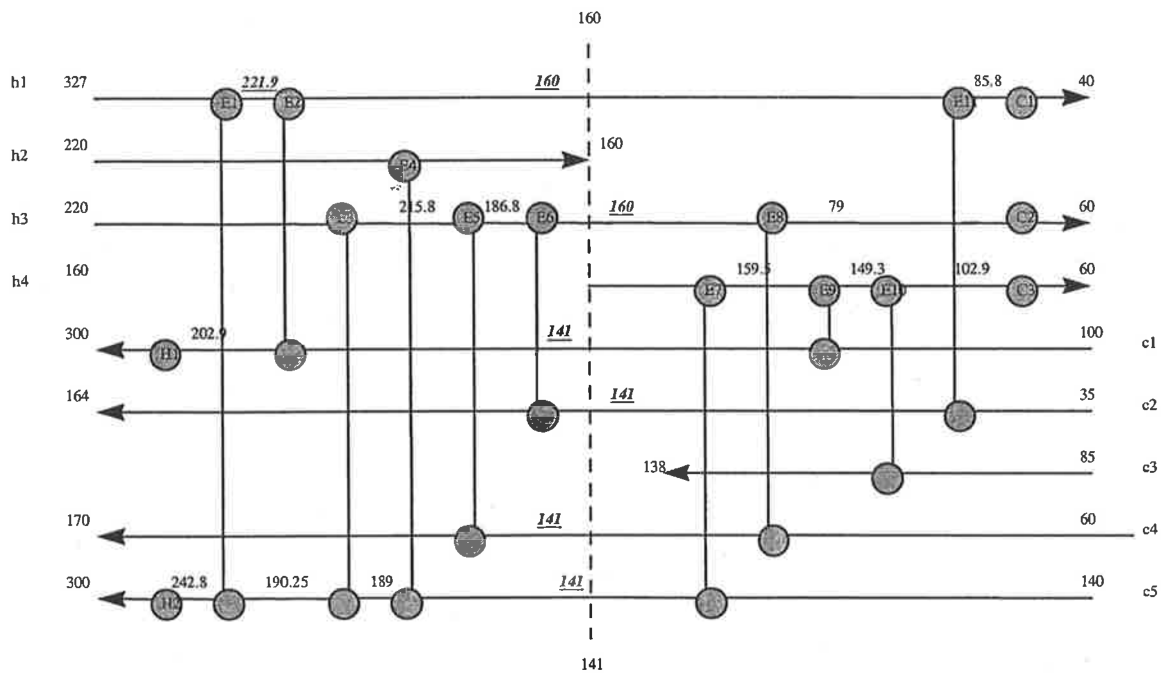


Figure 5.46: Pre-optimal designs, the total annual cost:$2,356,884

The match matrix for node 2-1 is presented in Table 5.26. The initial design involves matches h1-c1, h3-c4 and h4-c3 (Figure 5.48). The remaining part of node 2-1 includes a single hot stream h4. Hot stream h4 matching is relaxed by removing the h4-c3 unit. Cold streams c5, c2 and c3 then sequentially match with h4 in the order of their enthalpy change (Figure 5.49).

The pre-optimal design for node 2 costs $641,930. Obviously, cooler C1 in node 2-1 can merge with C4 in node 2-2. As well, E2 and E6 can merge into a single unit likewise E3 and E8 (Figure 5.50). Only a single variable (the temperature of cold stream c2 between E3 and E6) remains to be optimised. The optimal design for node 2 is shown in Figure 5.51. It achieves the total annual cost $615,310 which is less than the level-two design presented in Figure 5.40 ($621,870).

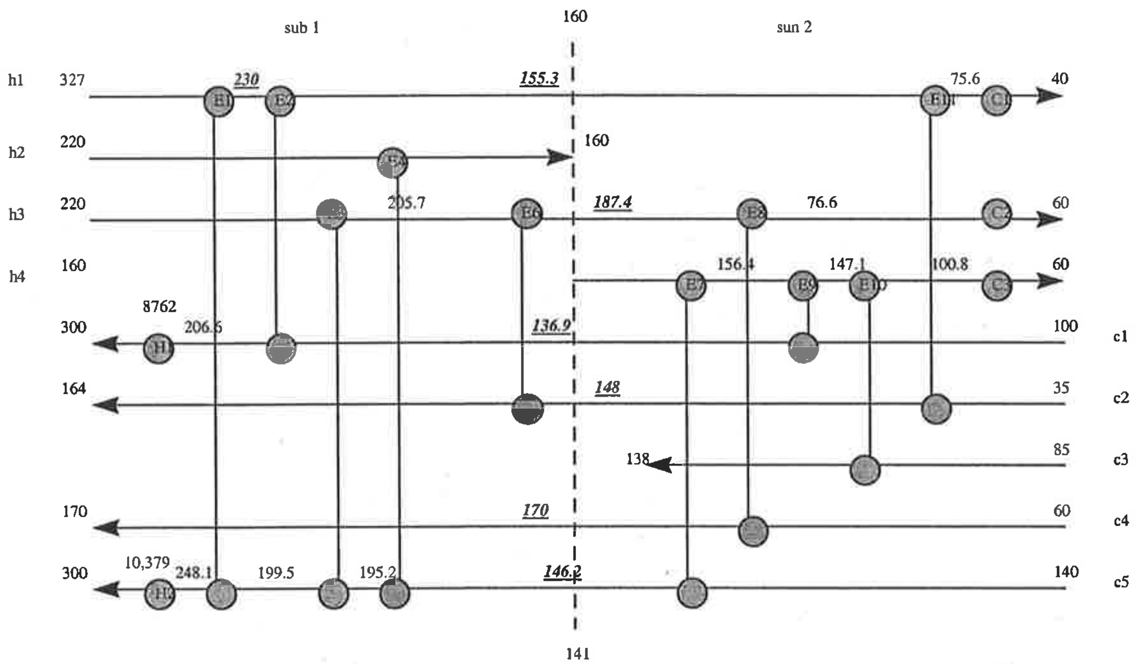


Figure 5.47: Final design, the total annual cost:$2,315,720

Table 5.25: The match matrix for node 2-2

	c2	c3	c4
h1	87971	302707	99989
h3	98343	311308	45531
h4	258918	277372	274097

Table 5.26: The match matrix for node 2-1

	c1	c2	c3	c4	c5
h1	44033	41542	826298	41833	48562
h3	173083	62497	882569	28817	30350
h4	165666	170718	132245	172383	181584
hot utility	286987	201160	927245	172526	14244
hot utility	286987	201160	927245	172526	14244

The combination of the two designs of the child nodes is presented in Figure 5.51. If Ahmad and Linnhoff's design (1989) is divided into two sub systems at the pinch (Figure 5.53), then the designs for two nodes generated by this new method is almost identical in structure. The design for node 2 possesses an identical structure to the design by Ahmad and Linnhoff. A minor difference is the load on heat exchanger E12. Ahmad and Linnhoff's design for node 2 costs $628,760. Compared to a total annual cost $615,310 for the current design. For node 1, the two designs exploit different matching orders for sequential matches. The design by Ahmad and Linnhoff costs $1,736,600 compared to $1,735,060 for the network devised by the new method.

Obviously in the design presented in Figure 5.51, E2 and E7 may merge into a single exchanger. Following this merging, six partition temperatures and one stream-split ratio are optimised. The final design is shown in Figure 5.52. The partition temperature for c4 is raised from 141 °C to 170 °C, and unit E5 is removed (zero load).

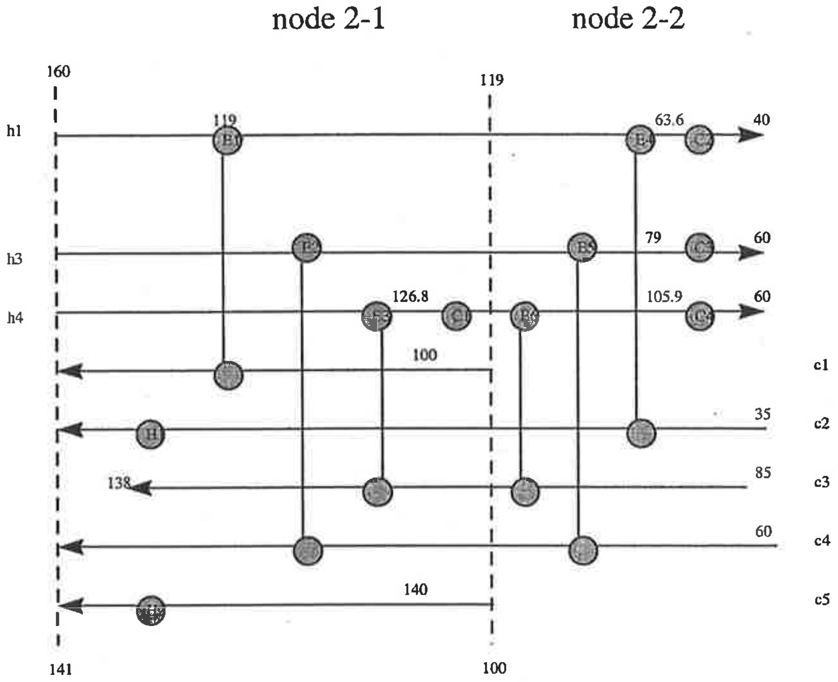


Figure 5.48: The initial design for node 2-1 and 2-2.

The designs from Ahmad and Linnhoff, and Suaysompol are illustrated in Figures 5.53 and 5.54, respectively. When compared to their designs, all designs generated by the new method (Figures 5.42, 5.47 and 5.52) show a reduced total annual cost, even in the case of the pre-optimal designs (Figures 5.46 and 5.51). The total annual cost is reduced from $2,363,770 for Ahmad and Linnhoff's design and $2,462,580 for Suaysompol's design to $2,286,820 for the new method. The hot utility consumption is reduced from 21.2 MW to 19.0 MW. A summary of the designs is presented in Table 5.27.

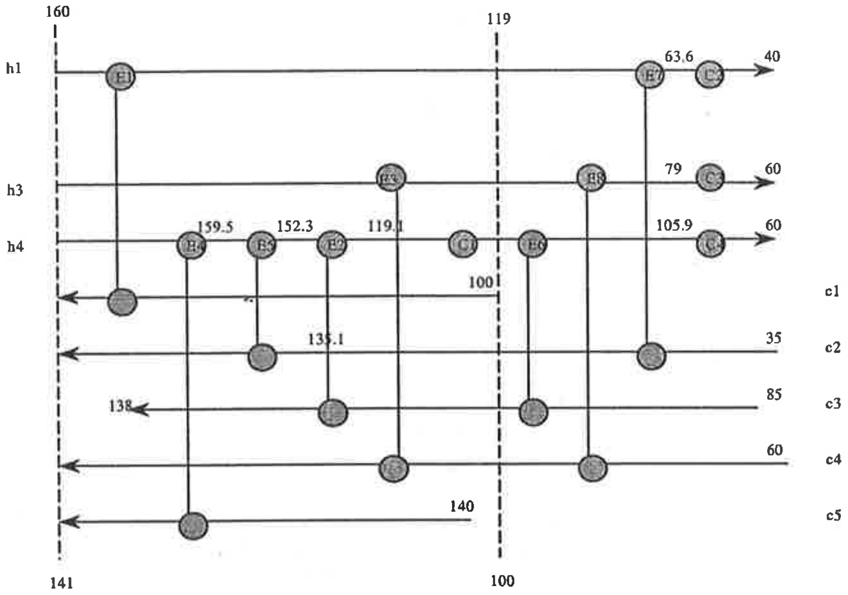


Figure 5.49: Combination of the design for two child nodes

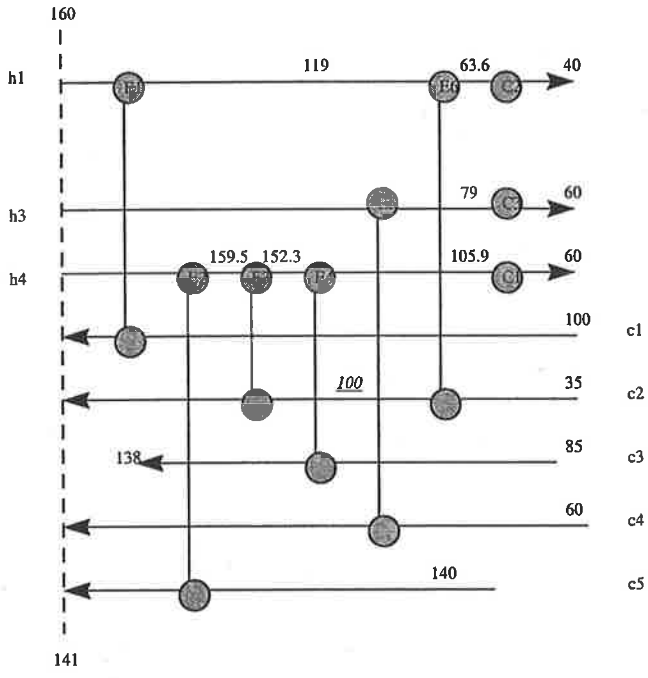


Figure 5.50: Pre-optimal design for node 2.

This example also demonstrates the benefits of decomposition in reducing the total annual cost and utility consumption for pre-optimal design. The process continues until all leaf nodes only require hot or cold utility. In this example, decomposition with three leaf nodes resulted in a design with 15 units and the total annual cost $2,315,720. Decomposition with four leaf nodes produced a design with 17 units and a total annual cost $2,288,430. Although the four leaf node design is slightly cheaper (1.2% less) than three leaf node design, the increased number of units makes the network more complicated with the possibility of increased maintenance.

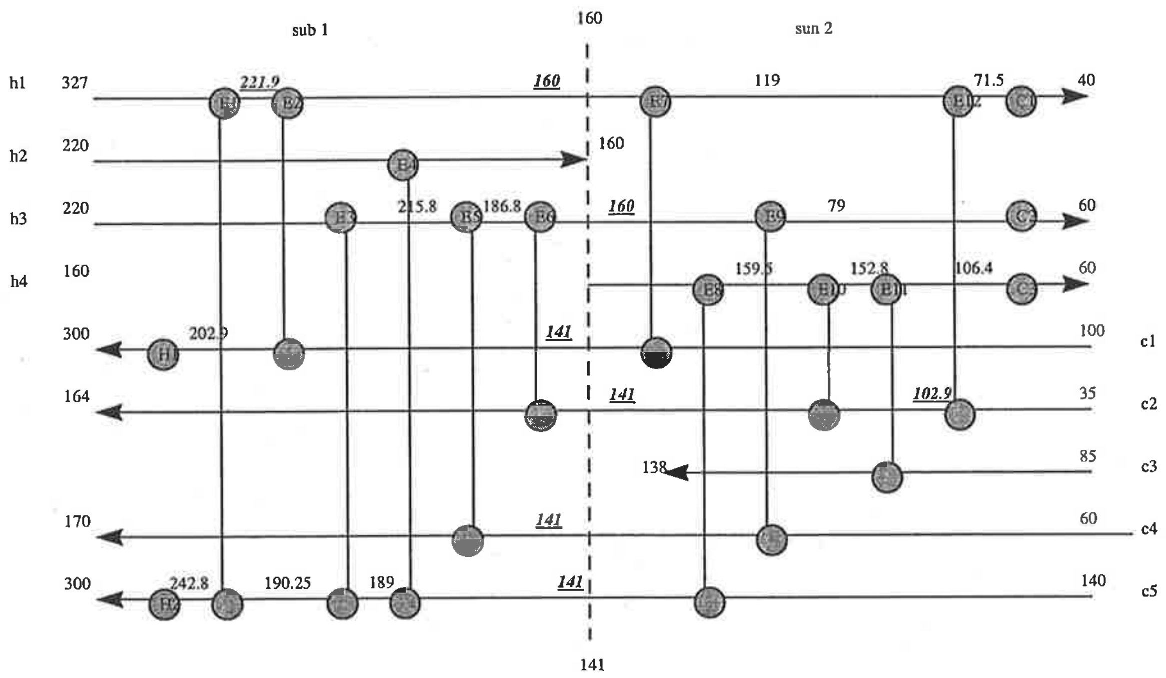


Figure 5.51: Combination of two designs for child nodes, the total annual cost: $2,350,330

Normally, an increase in the number of leaf nodes causes a commensurate rise in the number of the heat exchangers and consequently a more complex network. When the leaf nodes requires a single type of utility, further decomposition may decrease the cost, but utility consumption will not fall and number of exchangers may become excessive. A compromise is clearly required.

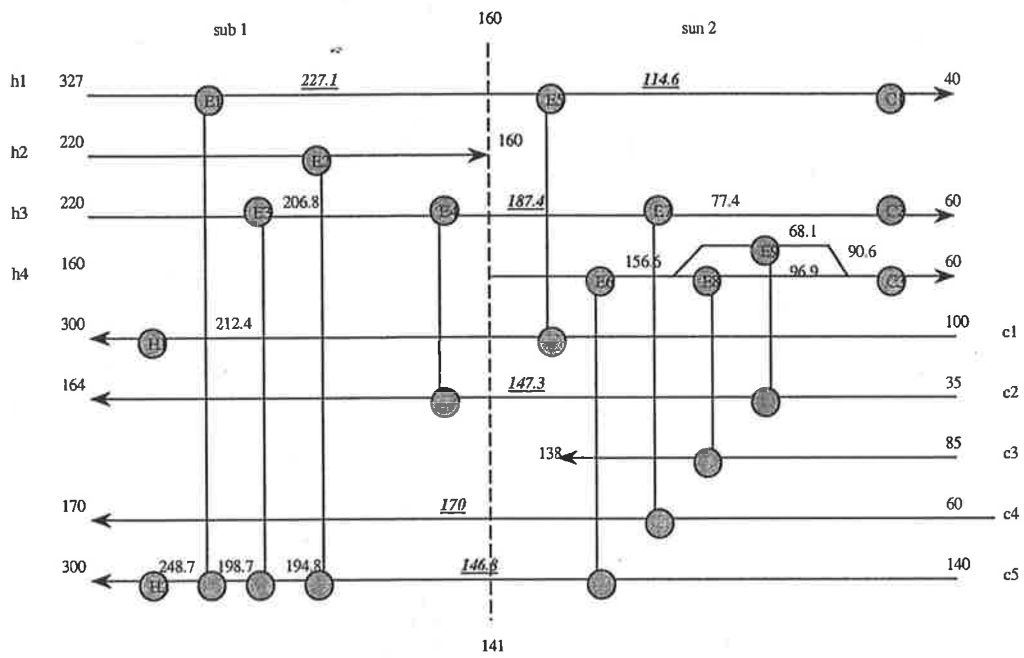


Figure 5.52: Final design, the total annual cost:$2,286,820

Table 5.27: Summary of different designs

Design method	Num. Of units	Hot utility(MW)	The total annual cost($)
New method (two leafs)	13	20.1	2,333,360
New method (three leafs)	15	19.1	2,315,720
New method (four leafs)	17	19.0	2,286,820
Ahamd and Linnhoff	17	21.2	2,363,770
Suaysompol	13	21.2	2,462,580

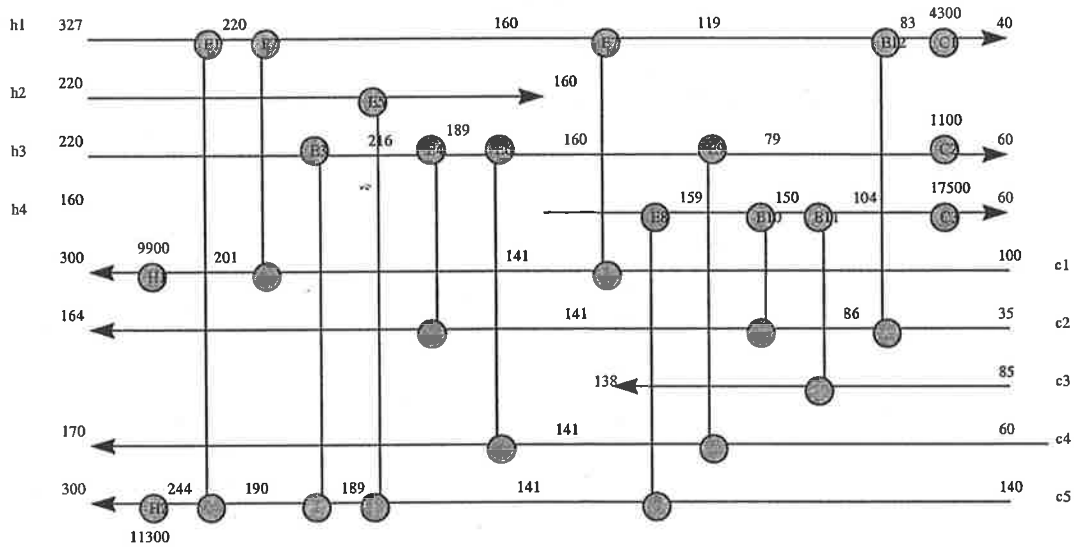


Figure 5.53: Design by Ahmad and Linnhoff (1989), the total annual cost: $2,363,771

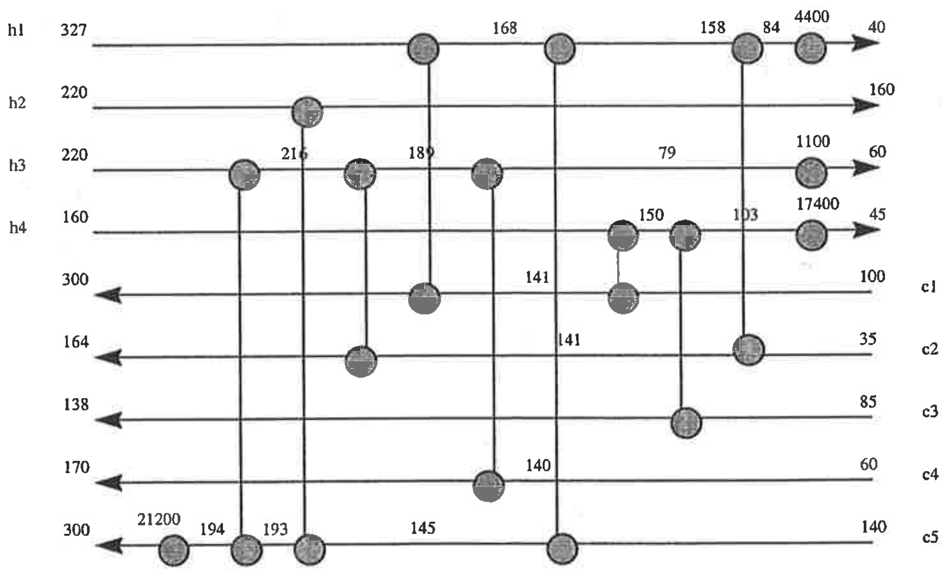


Figure 5.54: Design from Suaysompol et al (1991),the total annual cost:2,462,578

5.5.2.5 Case Study 7: The Aromatics Plant (South America economics)

In this case study, the aromatic plant is reconsidered using different utility costs and a different interest rate. The cost of energy is substantially reduced. The problem has been studied by Linnhoff and Ahmad (1989), and Suaysompol (1991). The relevant cost data are summarized below:

Exchanger cost($) = $700A^{0.83}$
Plant life : 5 years
Interest rate:13%
Cost of oil: $ 45.66/kW yr.
Cost of water: $ 6.37/ kW yr.

Design for the root node

The match matrix for the root node is presented in Table 5.28. The resulting initial design involves matches h1-c1, h2-c5, h3-c2 and h4-c3. The cold stream c4 is heated by hot utility (Figure 5.36).

The remaining part of the initial design includes h1, h3, h4, c4 and c5. Two matches are feasible (h1-c4 and h4-c4). Match h1-c4 is chosen applying match selection procedures (Figure 5.36). No other feasible matches are available following this match. The design using South American economics is identical to the design using European economics (Figure 5.36). However cheaper utility costs and higher interest rate alter the total annual cost to $2,030,520. The cost of utility is $1,326,280 approximately about 65 percent of the total annual cost. Decomposition for the root node is required.

Table 5.28: The match matrix for the root node

	c1	c2	c3	c4	c5
h1	248926	197679	153819	211763	930122
h2	576901	35154	453619	51300	1185444
h3	756574	-60600	587195	70802	1444375
h4	1099865	390488	365338	412867	1831772
hot utility	966301	426014	872619	312522	1548511

Design of the level-two nodes

The network is decomposed using the previous optimal HRAT. The match matrix for node 1 is presented in Table 5.29. The initial design involves matches h1-c1, h2-c5 and h3-c4 and is identical to the design derived using European economics (Figure 5.37).

Matches h1-c5 and h3-c2 are chosen for the initial design of the remaining part using the match-selection procedure. Further matches are not possible. The design for node 1 is identical to that shown in Figure 5.38. The utility cost for the design is $978,720, roughly 72 percent of the total annual cost $1,350,200.

Table 5.29: The match matrix for node 1

	c1	c2	c4	c5
h1	175230	156665	163939	833069
h2	733661	107383	138437	1179007
h3	640209	41528	43921	1399797
hot utility	775044	77525	83793	1539184

The match matrix for node 2 is presented in Table 5.30, leading to an initial design involving matches h1-c2, h3-c4 and h4-c3. Cold stream c1 and c5 are heated to their target temperatures by hot utility (Figure 5.39).

The remaining part of the design possesses a single hot stream h4. A sequential match problem must be considered. Hot stream h4 matching is relaxed by removing the match between hot stream h4 and cold stream c3. Cold stream c1, c3 and c5 sequentially match with hot stream h4 in the order of enthalpy change of the streams. The design for node 2 is identical to the design shown in Figure 5.40. The energy cost for node 2 is $145,680 - 22 percent of the total annual cost $655,730.

The combination of the two designs (node 1 and node 2) costs $2,007,760. This design can be further simplified by merging the coolers in the stream h3, and the matches between hot stream h3 and cold stream c4. This simplification reduces the cost to $1,986,540 (Figure 5.55). The total annual cost may be reduced to $1,952,750 by optimising partition temperatures. Heat exchangers E5 and E6 are eliminated from the design as their duties fall to zero (Figure 5.56).

Table 5.30: The match matrix for node 2

	c1	c2	c3	c4	c5
h1	145263	118337	921531	124439	127037
h3	189727	192749	898405	78383	63448
h4	365733	343917	365338	355152	364742
hot utility	194784	349877	872619	230028	9804
hot utility	194784	349877	872619	230028	9804

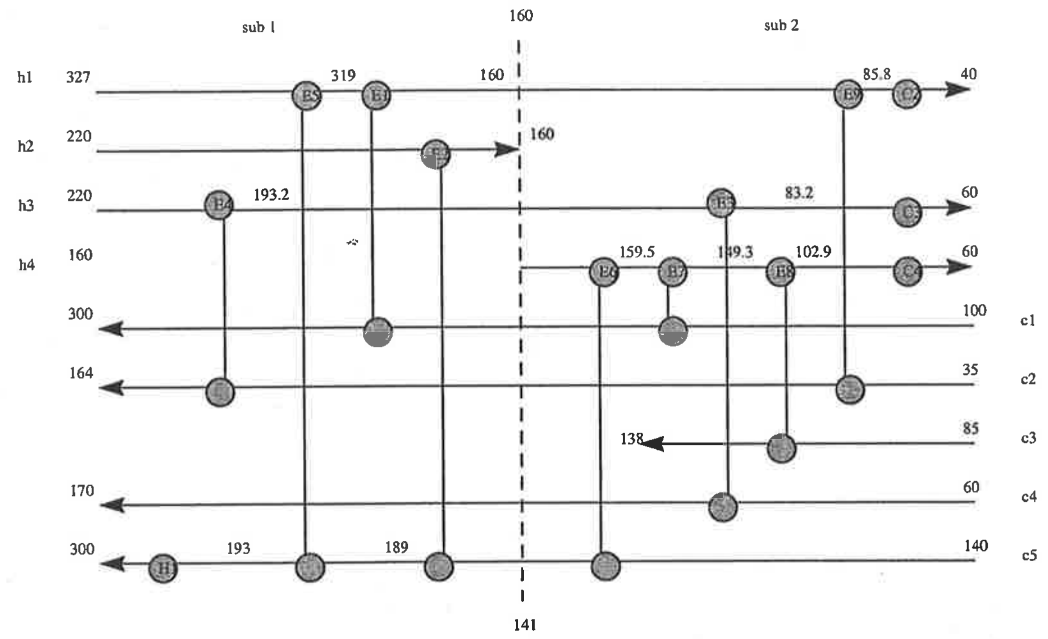


Figure 5.55: Pre-optimal design for the level-two decomposition.

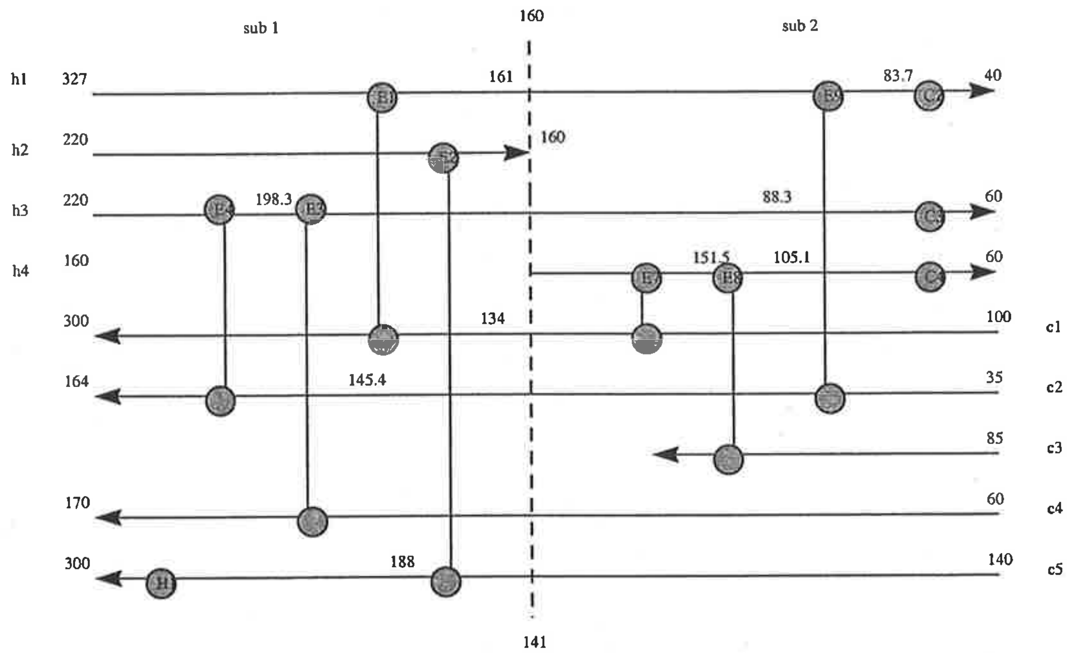


Figure 5.56: Design for the level-two decomposition, $1,952,750

Design for the level-three nodes

As node 1 design is an energy-cost dominant design, further decomposition is required. To minimise the total number of the streams in nodes (nodes 1-1 and 1-2), the partition temperatures are set at 220 °C for hot streams and 201 °C for cold streams.

The match matrix for node 1-1 is presented in Table 5.31. Based on this match matrix, a design with match h1-c5 is found for node 1-1 (Figure 5.43).

The match matrix for the node 1-2 is presented in Table 5.32. It produces an initial design with matches h1-c1, h2-c5 and h3-c4 (Figure 5.43). The remaining part of node 1-2 include only a single hot stream h3, hence, it is a sequential match problem. After relaxing the matching stream h3, stream c2, c4 and part of c5 sequentially match with c3 in the order of target temperatures of the cold streams. The combination of the designs for the two child nodes achieves the total annual cost $1,319,210 (Figure 5.44). As well, the heater H3 in the node 1-2 may merge with the heater H2 in node 1-1.

Two partition temperatures in the pre-optimal design of node 1 are then optimised. Only one is a manipulated variable. The optimal design for node 1 is identical to the design shown in Figure 5.45. The total annual cost is $1,319,150 - less than the cost ($1,350,200) of the level-two design.

Table 5.31: The match matrix for node 1-1

	c1	c5
h1	120097	531639
hot utility	492966	976833

Table 5.32: The match matrix for node 1-2

	c1	c2	c4	c5
h1	74581	68906	76129	337088
h2	243731	107383	125842	205820
h3	150382	41528	43921	430571
hot utility	287568	77525	83793	572111

The combination of the designs for nodes 1 and 2 is presented in Figure 5.57. Further merging is not required for this pre-optimal design and the total annual cost is $1,974,880. Following optimising the partition temperatures, the final optimal design is discovered (Figure 5.58). It costs $1,947,210. Heat exchangers E5 and E7 are removed from the design as their duties fall to zero.

As in the case with European economics, node 2 is partitioned at 119 °C / 100 °C. For sub system 2-2, the match matrix is presented in Table 5.33. The initial design involves matches h1-c2, h3-c4 and h4-c3. Further feasible matches are no longer available. The design for sub system 2-2 is shown in Figure 5.48.

Table 5.33: The match matrix for node 2-2

	c2	c3	c4
h1	92199	240260	96495
h3	82120	228435	50631
h4	226294	252514	234495

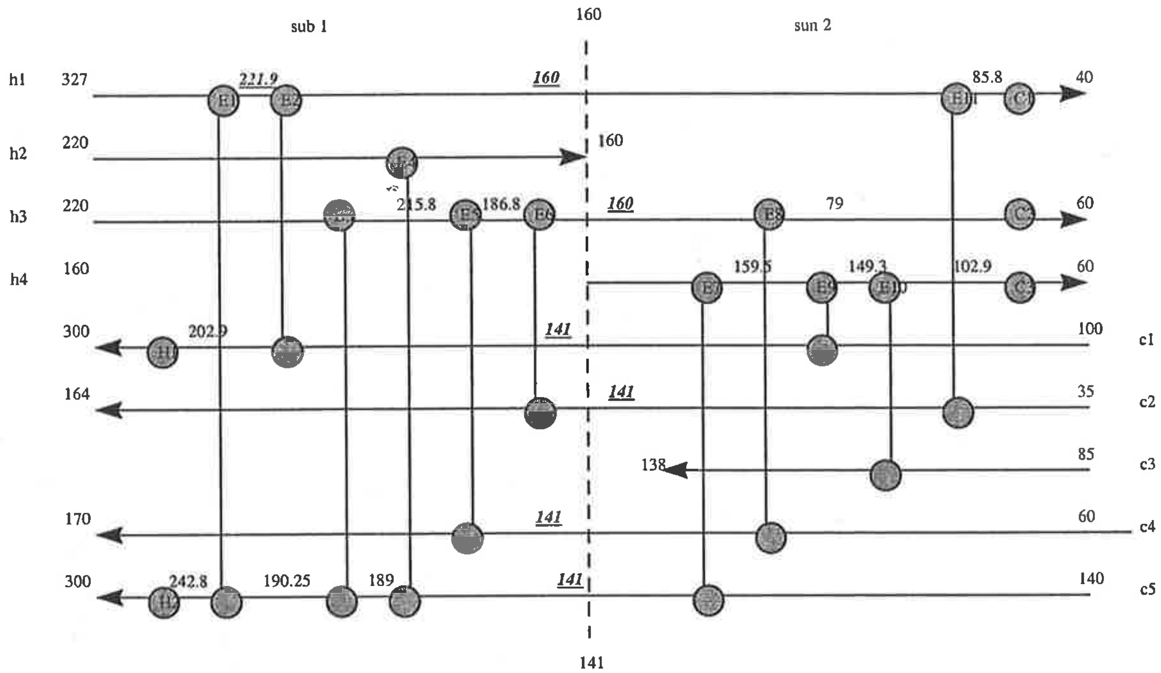


Figure 5.57: Pre-optimal designs, the total annual cost:$1,974,880

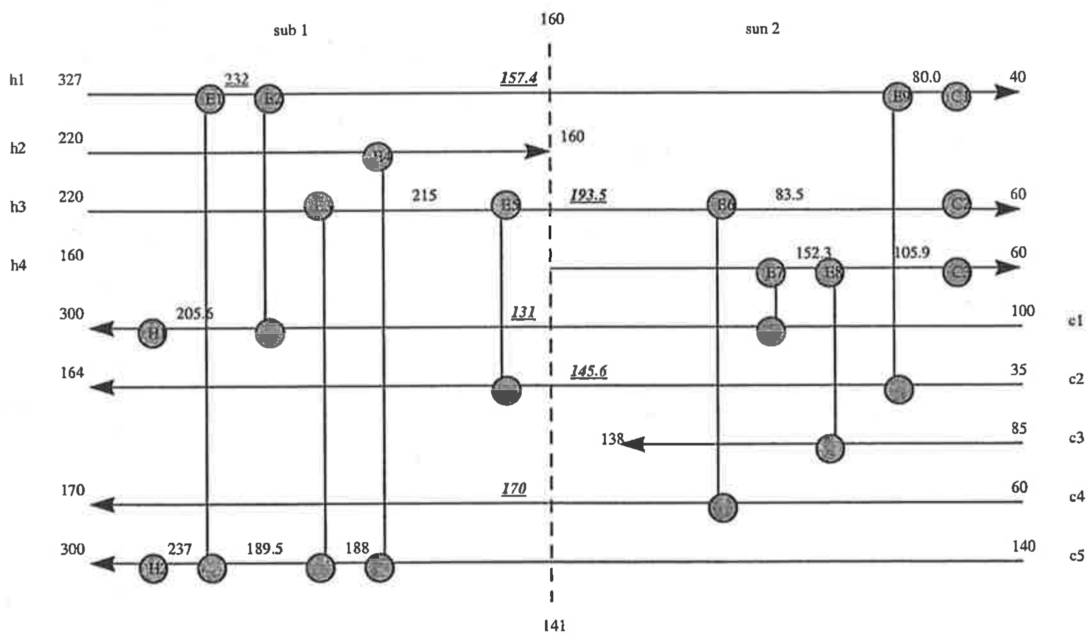


Figure 5.58: Final design, the total annual cost:$1,947,210

The match matrix for node 2-1 is presented in Table 5.34. The resulting initial design involves matches h1-c1, h3-c4 and h4-c3 (Figure 5.48). The remaining part of node 2-1 includes a single hot stream h4. Relaxing the matching of the hot stream h4, allows sequential matching with c5, c2 and c3 in the order of the stream enthalpy change. The design for node 2 is identical to the design in Figure 5.49. After merging C1 with C4, the design costs $677,250.

Table 5.34: The match matrix for node 2-1

	c1	c2	c3	c4	c5
h1	54371	45264	586829	43613	40839
h3	149887	61212	613997	35583	26394
h4	144247	144455	148093	144499	144778
hot utility	194784	136680	627275	117283	9804
hot utility	194784	136680	627275	117283	9804

Obviously, heat exchangers E2 and E6 can merge into a single unit and E3 and E8 can likewise merge into one unit. The simplified design is shown in Figure 5.50 with a total annual cost $648,270. A single variable, (the temperature of cold stream c2 between E3 and E6), needs to be optimised. The resulting design for node 2 is shown in Figure 5.51. The total annual cost for the design is $647,630 slightly less than the cost $655,730 for the design in level two.

Combination of two designs produces a design with total annual cost $1,966,780 (Figure 5.59). Again, E2 and E7 may be collapsed into a single heat exchanger. The resulting design costs $1,952,580. Eight parameters are then optimised and the final optimal design is presented in Figure 5.60 (the total annual cost $1,930,350). As the duties for E5 and E8 have been reduced to zero, they are removed from the final design.

The design of Ahmad and Linnhoff, and that of Suaysompol are illustrated in Figure 5.61 and Figure 5.62 respectively. The final design (Figure 5.60) from the new method provides an improved network with reduced total annual cost. The total annual cost falls from $2,008,280 for Ahmad and Linnhoff's design and $2,024,750 for Suaysompol's design to $1,930,350. A summary of the different designs is presented in Table 5.35.

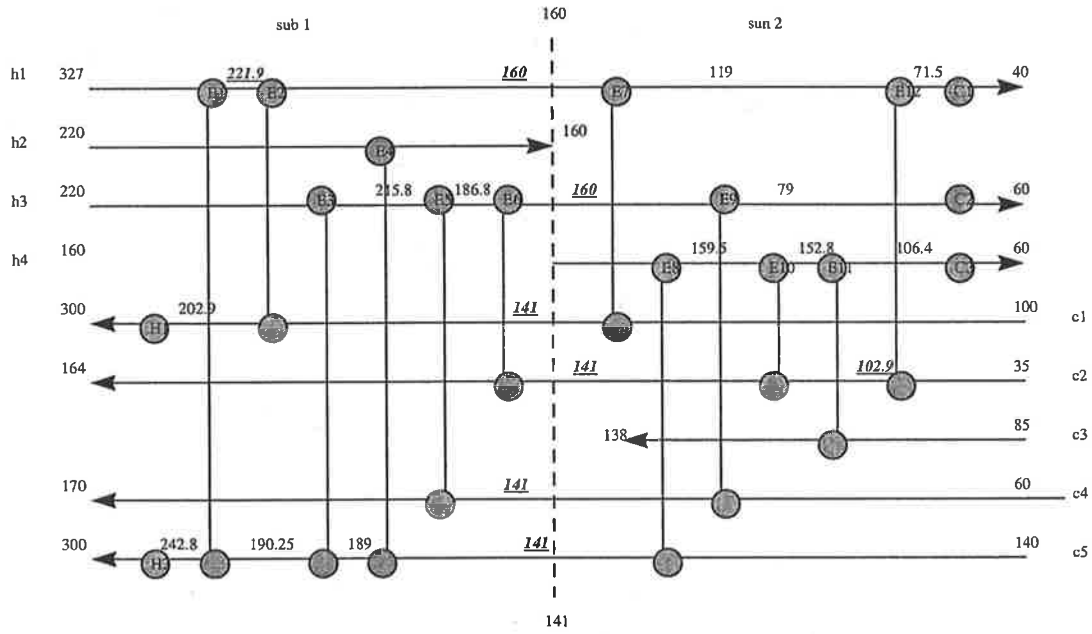


Figure 5.59: Pre-optimal designs, the total annual cost:$1,966,782

Table 5.35: Summary of different designs

Design method	Num. Of units	Hot utility(MW)	The total annual cost($)
New method (two leaves)	11	22.4	1,952,750
New method (three leaves)	14	22.0	1,947,210
New method (four leaves)	14	21.7	1,930,350
Ahmad and Linnhoff	18	27.3	2,008,280
Suaysompol	15	25.0	2,024,750

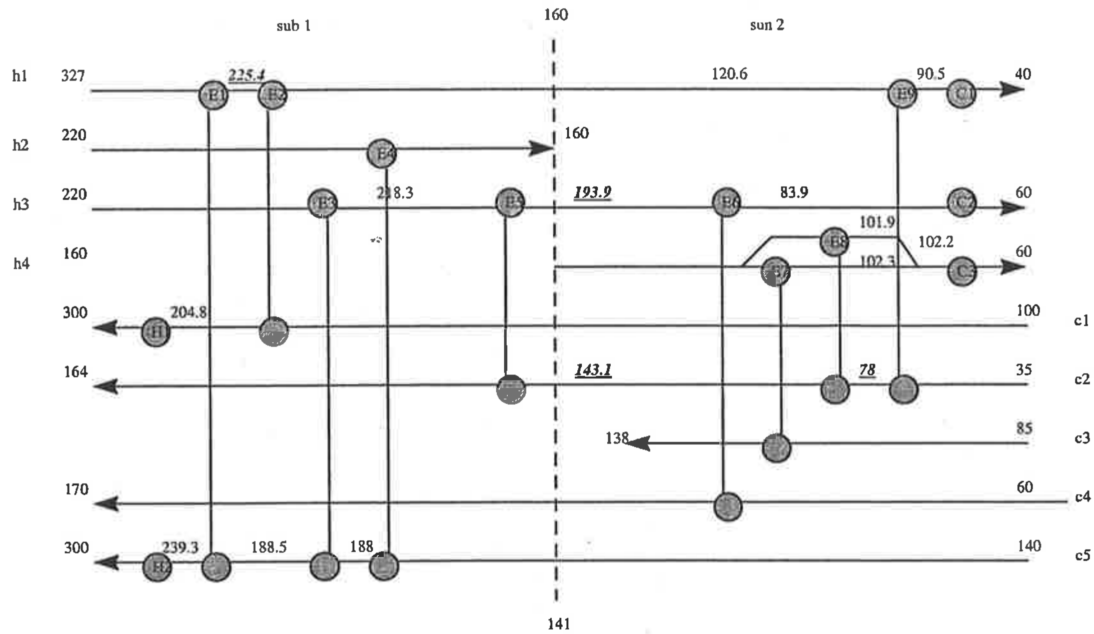


Figure 5.60: Final design, the total annual cost:$1,930,350

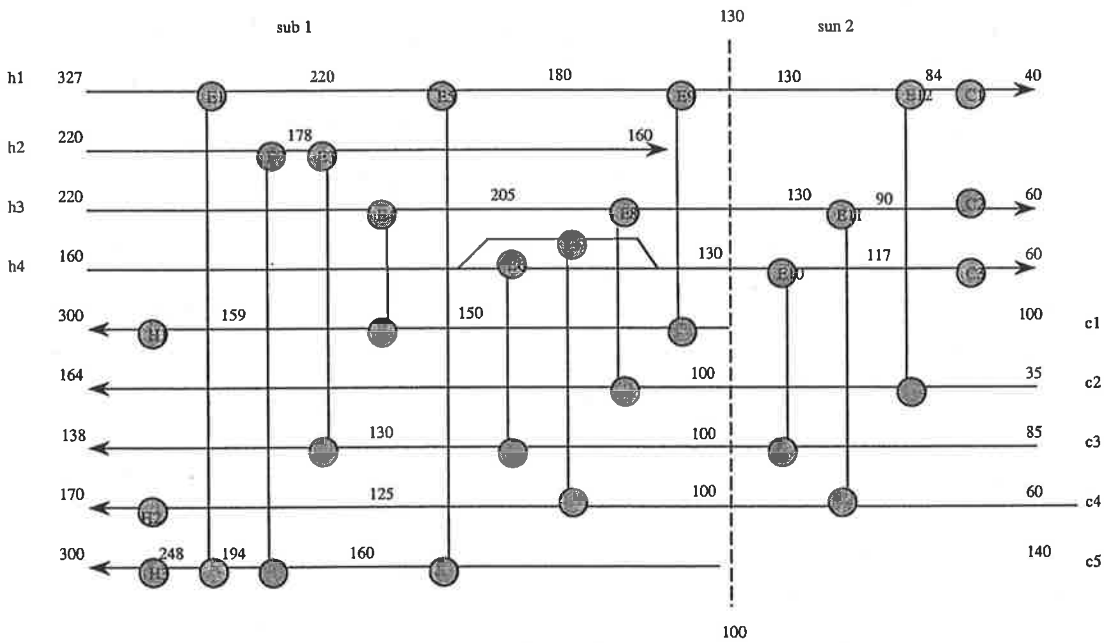


Figure 5.61: Design from Ahmad and Linnhoff (1989), the total annual cost: $2,008,280

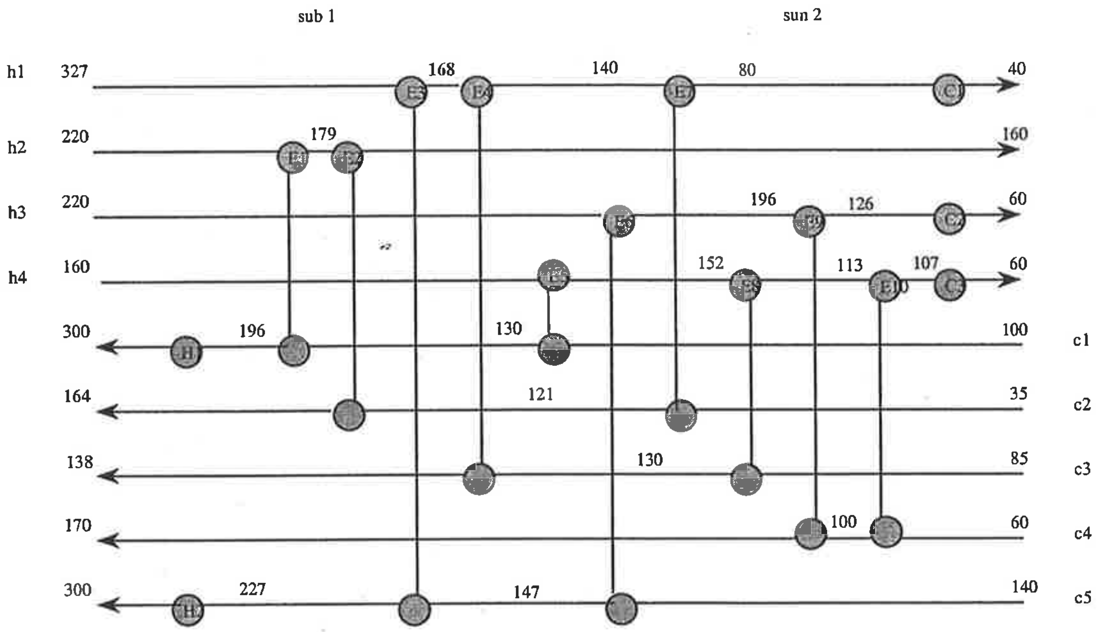


Figure 5.62: Design from Suaysompol et al (1991), the total annual cost:2,024,750

5.5.3 Network Problem Involving Constraints

Imposed constraints based on safety or layout considerations may influence the choice of potential matches between hot streams and cold streams. For example, a match may be forbidden or imposed.

In the recursive synthesis method, matches in any initial designs or subsequent designs of remaining part are selected by the match-selection model. The presence of a forbidden match means that this match must never be selected in any initial designs or subsequent designs of remaining part. To achieve this objective, the cost index for this match in the match matrix is assigned to an arbitrarily large value. This will guarantee the match is not selected. By contrast, if the cost index of a match in the match matrix has been assigned to zero or a very low value, the match will be guaranteed of selection. This goal may be achieved by scaling the true cost of a match.

The following case studies demonstrate the new method's ability to easily solve problems with constraints.

5.5.3.1 Case Study 8

This problem was proposed by Cerda and Westerberg (1983), and studied by Trivedi et. al. (1988) and Suaysompol et. al. (1991). The relevant stream data are presented in Table 5.36. The data is a threshold problem and as a consequence, only hot utility is required. Designs without constraints and with constraints have been undertaken.

Table 5.36: Stream data

Stream	h1	h2	h3	steam	c1	c2	c3	c4	water
Tin(°C)	310	244	238	330	93	38	149	66	20
Tout(°C)	149	93	66	320	205	221	205	138	30
Cp (kW/K)	12.53	8.32	6.95		8.45	8.44	19.65	15.5	
h (W/m^2K)	0.7	0.7	0.7	1.25	0.7	0.7	0.7	0.7	0.7

Exchanger cost ($) : $4939A^{0.55}$

Annualised factor: 10%

Cost of steam: 0.0057 $/kWh = 45.44 $/kW yr.

The results of Supertargeting for this case are presented in Table 5.37. When HRAT is set equal to 28 K the pinch at 66 °C for hot and 38 °C for cold, respectively. This example is a threshold problem and only hot utility is required.

Table 5.37: Results of Supertarget algorithm

ΔT (K)	hot utility (kW)	cold utility (kW)
≤ 28	238.27	0

Design for the root node

The match matrix for the root node is presented in Table 5.38. The initial design involves the matches h1-c1, h2-c4 and h3-c2, with c3 heated by utility (Figure 5.63).

Table 5.38: The match matrix for the root node

	c1	c2	c3	c4
h1	8308	6405	58564	7493
h2	49349	19199	58279	6534
h3	50608	22817	59218	59470
hot steam	44970	72668	52324	52576

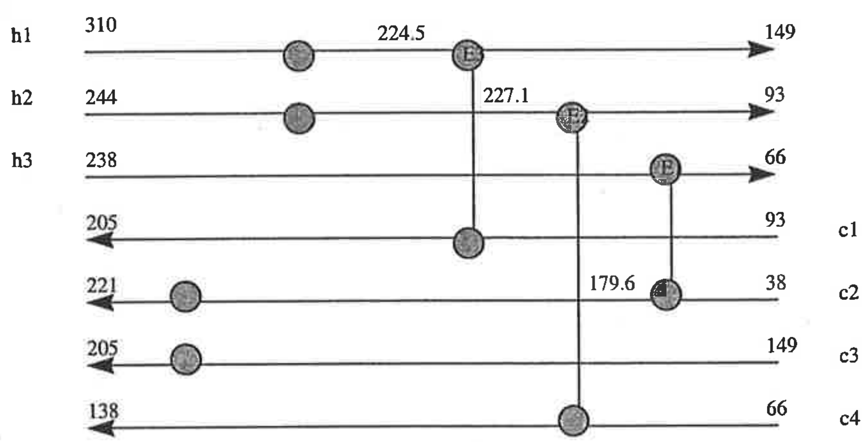


Figure 5.63: The initial design for the root node

The match matrix for the remaining part of the problem is presented in Table 5.39. It suggests a design involving the matches h1-c3 and h2-c2. Additional hot streams are not available to exchange energy with the cold streams (Figure 5.64). This design is identical to the design proposed by Suaysompol et. al.(1991) with a total annual cost $32,210.

Table 5.39: the match matrix for the remaining part

	c2	c3
h1	4777	5106
h2	12143	46970

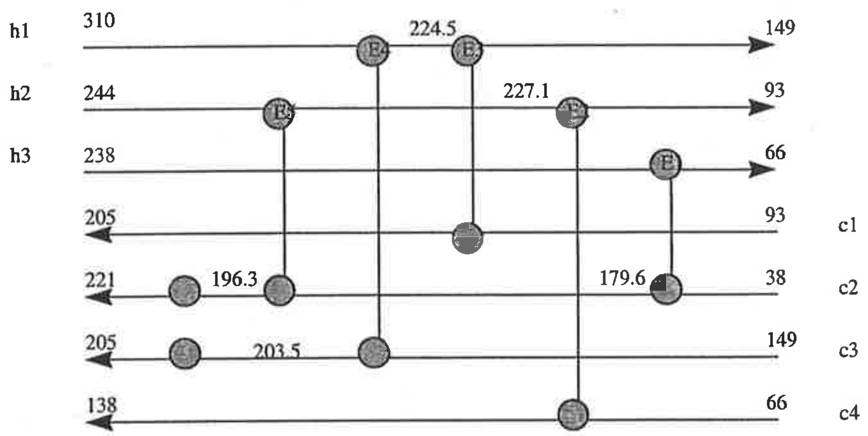


Figure 5.64: Final design for the root node

Design with constraints

Suppose that matches between h2-c2 and h3-c4 are forbidden. Then, the cost indices for these matches are set to an arbitrarily large value say $\$10^6$. The modified match matrix is presented in Table 5.40. An initial design is suggested involving match h1-c1, h2-c4 and h3-c2 with c3 heated by utility. This design is identical to the previous design (Figure 5.63).

Table 5.40: The match matrix for the root node with constraints

	c1	c2	c3	c4
h1	8308	6405	58564	7493
h2	49349	1000000	58279	6534
h3	50608	22817	59218	1000000
got	44970	72668	52324	52576

The match matrix for the remaining part is presented in Table 5.41. The initial design involves the matches h1-c2 and h2-c3. The remaining parts include hot stream h1 and cold stream c3 in a match. This design is shown in Figure 5.65 and is identical to a design proposed by Suaysompol et. al. (1991) with a total annual cost of \$34,330.

In this design, hot stream h1 sequentially matches with cold stream c1, c2 and c3. Driving forces may be improved by splitting. However, temperature constraints mean that c1 cannot participate in the stream splitting. Following splitting, the total annual cost is reduced to \$33,325 (Figure 5.66). A summary of the designs using different methods is presented in Table 5.42.

Table 5.41: The match matrix for the remaining part

	c2	c3
h1	4777	5106
h2	1000000	46970

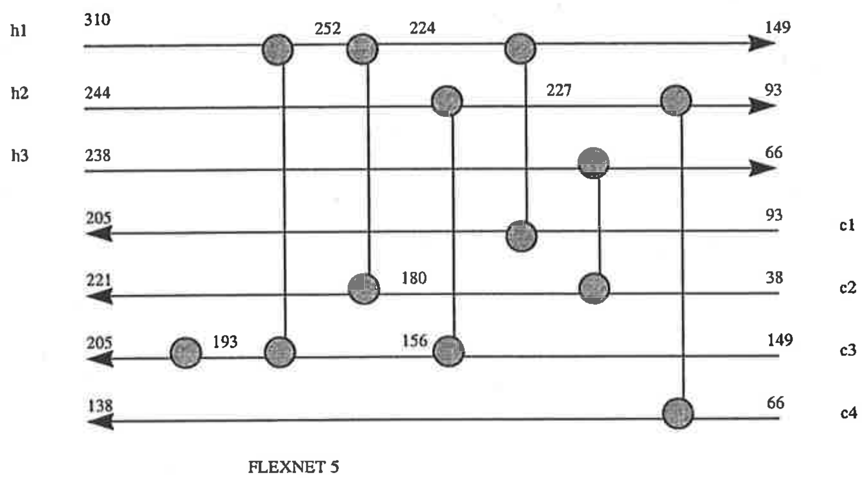


Figure 5.65: Design 1 by Suaysompol et. al. (1991)

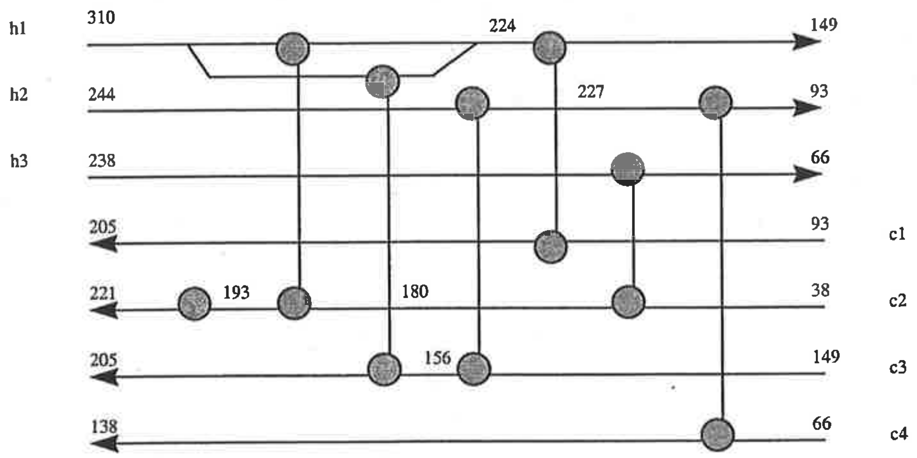


Figure 5.66: Final design

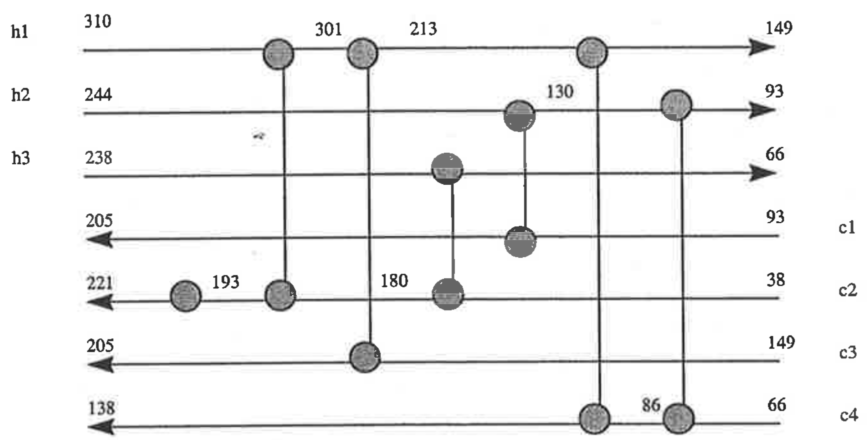


Figure 5.67: The design by Trivedi et al. (1988)

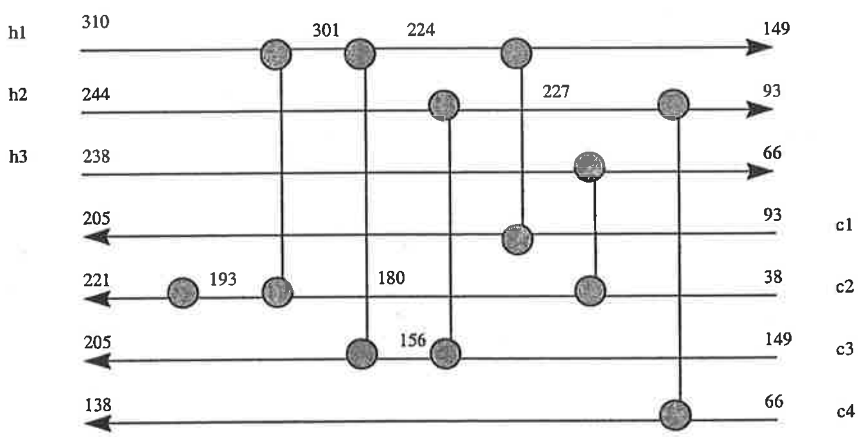


Figure 5.68: The design 2 by Suaysompol et. al.(1991).

Table 5.42: Summary of different designs

Method	No. of Units	The total annual cost (K$)
New method	7	33.33
Cerda and Westerberg	7	35.00
Trivedi et. al.	7	34.33
Suaysompol et. al. (1)	7	33.20
Suaysompol et. al. (2)	7	34.33

5.5.3.2 Case Study 9

This problem was studied by Cerda et al.(1983), Trivedi et al. (1988) and Suaysompol et al. (1991). In the original problem, the stream possesses different CP values in different temperature ranges. To simplify the data, the CP value for each stream is set to an average value. The stream data and relevant cost data are presented in Table 5.43.

Hot stream h2 is forbidden from matching the cold stream c1 above its bubble point. This corresponds to the temperature range of 180-250 °C for the cold stream c1.

Table 5.43: Stream data for case 9

Stream	h1	h2	stream	c1	c2	water
Tin(°C)	300	280	330	100	140	15
Tout(°C)	140	100	320	250	225	25
Cp(kW/K)	1.443	3.2		2.653	4.218	
Q(kW)	230.8	576		398	358.5	
h(W/m^{2}K)	700	700	1250	700	70	1050

Exchanger cost: ($) $4939A^{0.55}$

Annualised factor: 10%

Hot utility cost: 45.44 $/kW yr.

Cold utility cost: 6.38 $/kW yr.

Design for the root node

The match matrix for the root node is presented in Table 5.44. Without any constraints, the initial design involves matches h1-c2 and h2-c1 (Figure 5.69). No matches are possible for the remaining section of the design. Utility cost is $7,270, a contribution of about 49 percent of the total annual cost $14,530. Since the fraction of utility cost lies in the marginal area (very close to 50 percent), further decomposition is required for the root node.

Table 5.44: The match matrix for the root node without constraints

	c1	c2
h1	10284	9687
h2	5244	5477

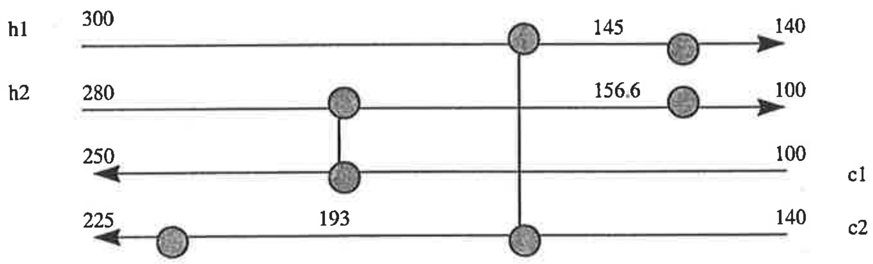


Figure 5.69: The design for the root node without constraints

If h2 can not match c1 above its bubble point, the initial design changes and is shown in Figure 5.70. The utility cost for this design is \$8,990, a contribution of 57 percent of the total annual cost \$14,530 and further decomposition of the root node is required.

Design for level-two nodes

The root node is decomposed into two child nodes (1 and 2). The partition temperatures of hot streams and cold streams are 160°C and 140°C, respectively.

The match matrix for node 1 without constraints is presented in Table 5.45. An initial design featuring matches h1-c1 and h2-c2 results. The remaining problem contains a single hot stream h2 and single cold streams c1 producing a match (Figure 5.71). The utility cost for this design is \$2,930, some 31 percent of the total annual cost of \$9,520. Further decomposition is unnecessary.

If the constraint is imposed for c1, the cost index for potential match h2-c1 is arbitrarily set at 10^6 (a sufficiently large number). The match matrix with the constraints is presented in Table 5.46. The initial design has matches h1-c1 and h2-c2 (Figure 5.72). As the match between h2 and c1 is forbidden, no matches are available for the remaining problem. Utility cost for the design is \$4,240 (about 39 percent of the total annual cost of \$10,690). Clearly, further decomposition of the root node is not required.

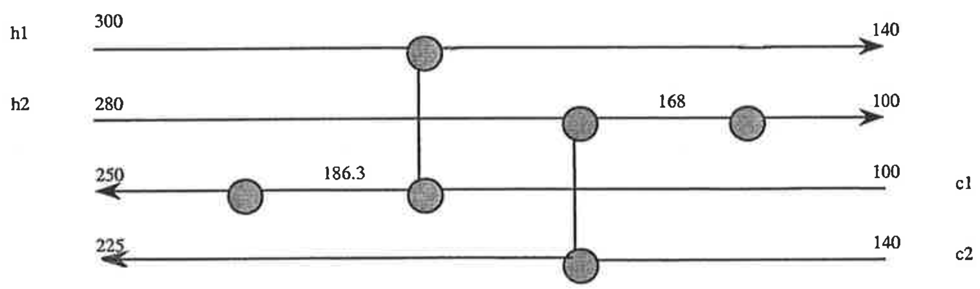


Figure 5.70: The design for the root node with constraints

Table 5.45: The match matrix for node 1 without constraints

	c1	c2
h1	6866	9838
h2	9825	3820

Table 5.46: The match matrix for the node 1 with constraints

	c1	c2
h1	6866	9838
h2	1000000	3820

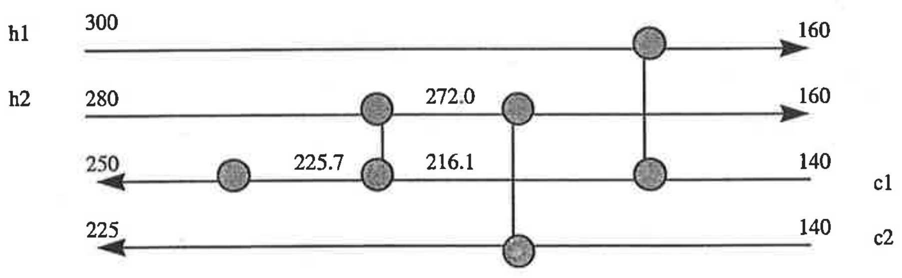


Figure 5.71: The design for the node 1 without constraints

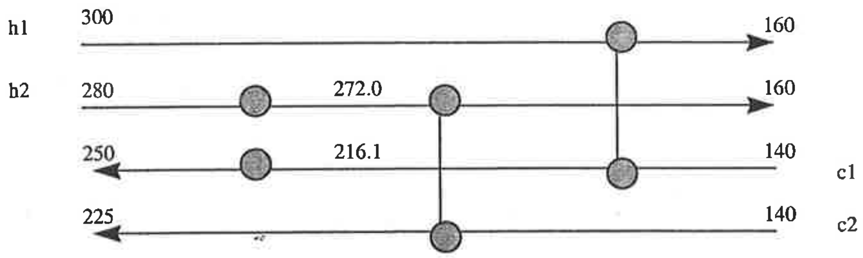


Figure 5.72: Design for the node 1 with constraints

Node 2 is unconstrained and includes two hot streams plus a single cold stream. The design for node 2 is shown in Figure 5.73.

The combination of designs for nodes 1 and 2 without constraints is shown in Figure 5.74. The total annual cost is $13,390. Three partition temperatures are then optimised to produce a final design (Figure 5.76). The total annual cost is reduced to $12,530.

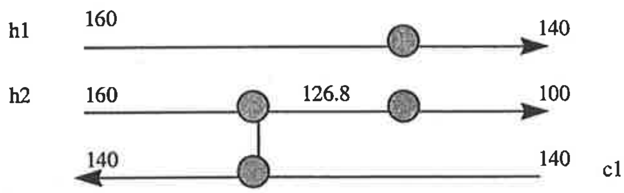


Figure 5.73: The design for the node 2

The combined design for node 1 and node 2 with constraints is illustrated in Figure 5.75. The total annual cost is $14,560. Three partition temperatures are next optimised providing a final design (Figure 5.77). The total annual cost is reduced to $13,020.

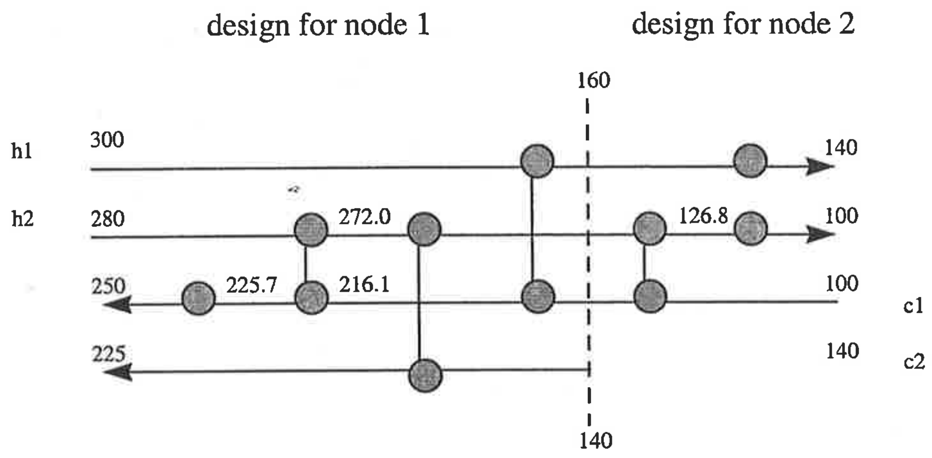


Figure 5.74: Pre-optimal design without constraints

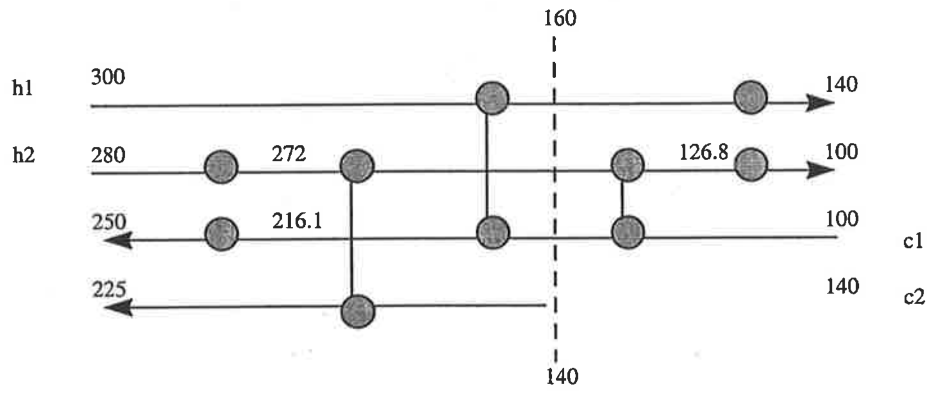


Figure 5.75: Pre-optimal design with constraints

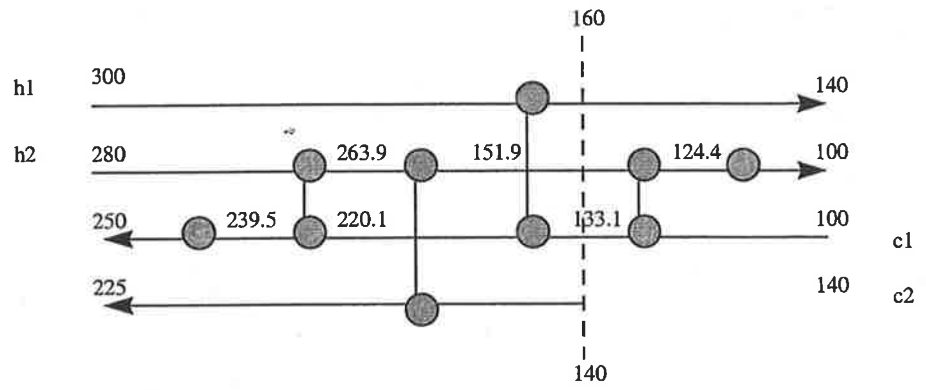


Figure 5.76: The design without constraints, $12,530

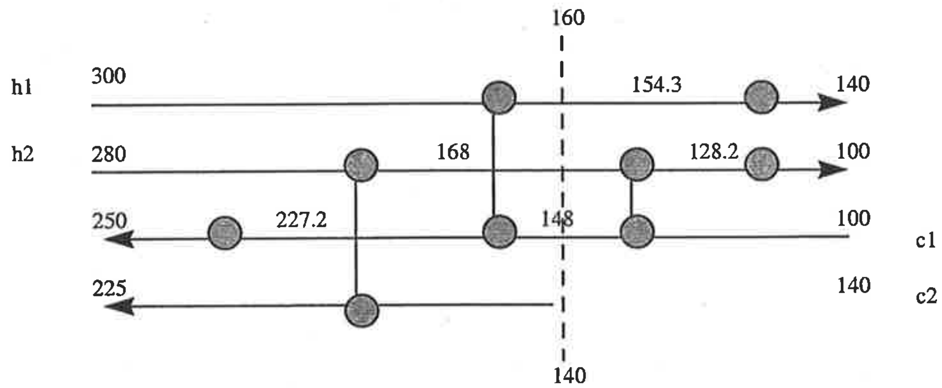


Figure 5.77: The design with constraints

5.5.3.3 Case Study 10

This case study is a practical example provided by Aspen Plus Web Home Page. The relevant stream and cost data are presented in Table 5.47 and 5.48.

Table 5.47: data for hot streams and hot utilities

Stream	h1	h2	h3	h4	h5	h6	h7	h8	mp	hp
Tin(°C)	182	70	147	99	142	54	48	112	126	198
Tout(°C)	93	49	146	93	38	48	38	38	126	198
Cp(kW/K)	47.19	1438.1	28700.	73.33	27.00	1683.3	65.00	57.03		
h (W/m^2K)	1.02	0.85	1.25	1.42	1.48	1.08	0.91	1.14	3.75	3.69
Q (MW)	4.2	30.2	28.7	0.44	2.7	10.1	0.65	4.22		

Table 5.48: data for cold streams and cold utility

Stream	c1	c2	c3	c4	c5	c6	c7	water
Tin(°C)	50	50	101	49	101	174	112	25
Tout(°C)	160	93	102	82	118	175	113	40
Cp(kW/K)	47.27	107.67	24000	100	94.12	22100	12800	
h (W/m^2K)	1.48	1.02	1.59	1.36	1.02	1.82	1.36	1.25
Q (MW)	5.2	4.63	24	3.3	1.6	22.1	12.8	

Exchanger cost \$ = 218.2A

Plant life time = 5

Interest: 10%

HP hot utility cost: 123.84 $/(kW.yr)

MP hot utility cost: 92.16 $/(kW.yr)

Cold water cost: 2.88 $/(kW.yr)

Annual factor: 0.263797

The supply temperatures for hot stream h6 and h7 are below 54 °C and no cold stream can exchange energy with them, hence, these two streams will be cooled by cold water and will not be considered in the design.

Design for the root node

The match matrix for root node is presented in Table 5.49. It produces an initial design involving matches h1-c7, h2-c4, h3-c3, h4-c1, h5-c5 and h8-c2. The match matrix for remaining parts is presented in Table 5.50. The design for the remaining parts involves matches h1-c2, h3-c7 and h5-c4. No further match is available.

The design for root node costs $4,106,840. The utility cost is $3,618,690 and it constitutes about 88 percent of the total annual cost. Hence, decomposition of the root node is required.

Table 5.49: Match matrix for the root node

	c1	c2	c3	c4	c5	c6	c7
h1	134269	47825	1939332	7977	13845	2781255	956144
h2	1700185	953642	2987673	748701	994258	4025717	2037904
h3	208132	95275	61139	97339	104427	2887154	91681
h4	176074	77367	2002313	7209	15278	2796408	1048408
h5	263926	147380	2104857	18339	16024	2797872	1102861
h8	351702	163142	2256652	31175	151195	2805256	1258329
hot	647454	433149	2262346	307355	155154	2081155	1234356

Table 5.50: Match matrix for remaining parts

	c1	c2	c4	c7
h1	169031	29765	56073	943350
h3	134848	18484	16993	400099
h5	175105	68450	58218	949425
hot	164156	129551	158556	938475

Design for the level-two nodes

The system is partitioned at 70 °C for hot streams and 50 °C for cold streams. The design for sub-system 1 (above the partition temperature) is again an utility cost dominant problem and the energy cost constitutes about 90 percent of the total annual cost. This sub system 1 is further decomposed at 121 °C for hot streams and 101 °C for cold streams. The design for sub-system 2 involves a single match h5-c4.

Design for the level-three nodes

Cold stream c6 is heated by hot utility HP (high pressure steam) and it does not participate in any matches.

Table 5.51: Match matrix for sub-system 1-1

	c1	c3	c5	c7
h1	13579	1997219	11191	966684
h3	219605	61271	104536	92173
h4	131805	2094168	7803	1065902
h5	412446	2130137	20773	1100793

The match matrix for sub-system 1-1 is presented in Table 5.51. The initial design for sub system 1-1 involves matches h1-c1, h3-c3, h4-c7 and h5-c5. Match matrix for its remaining parts is presented in Table 5.52 and its initial design involves matches h1-c5 and h3-c7. After this design, all hot streams are ticked off and no match is available.

Table 5.52: Match matrix for remaining parts of sub-system 1-1

	c5	c7
h1	8187	1049579
h3	17309	616479

The match matrix for sub-system 1-2 is presented in Table 5.53. Its initial design involves matches h4-c2 , h5-c4 and h8-c1. Design for its remaining parts involves a single match h1-c4.

Table 5.53: Match matrix for sub-system 1-2

	c1	c2	c4	water
h1	138404	312968	177795	165458
h5	132179	308490	173165	191628
h4	49174	245888	110662	128814
h8	14030	218643	83067	224761

Optimisation of the partition temperatures between sub-systems 1-1 and 1-2 produces a design for sub-system 1 which costs $3,786,020.

The design for sub-system 2 involves a single match h5-c4. Optimisation of partition temperatures between sub-system 1 and 2 produces a final design which costs \$4,064,530. This cost does not include the costs for streams h6, h7 and c6 which are heated or cooled solely with utilities (Figure 5.78).

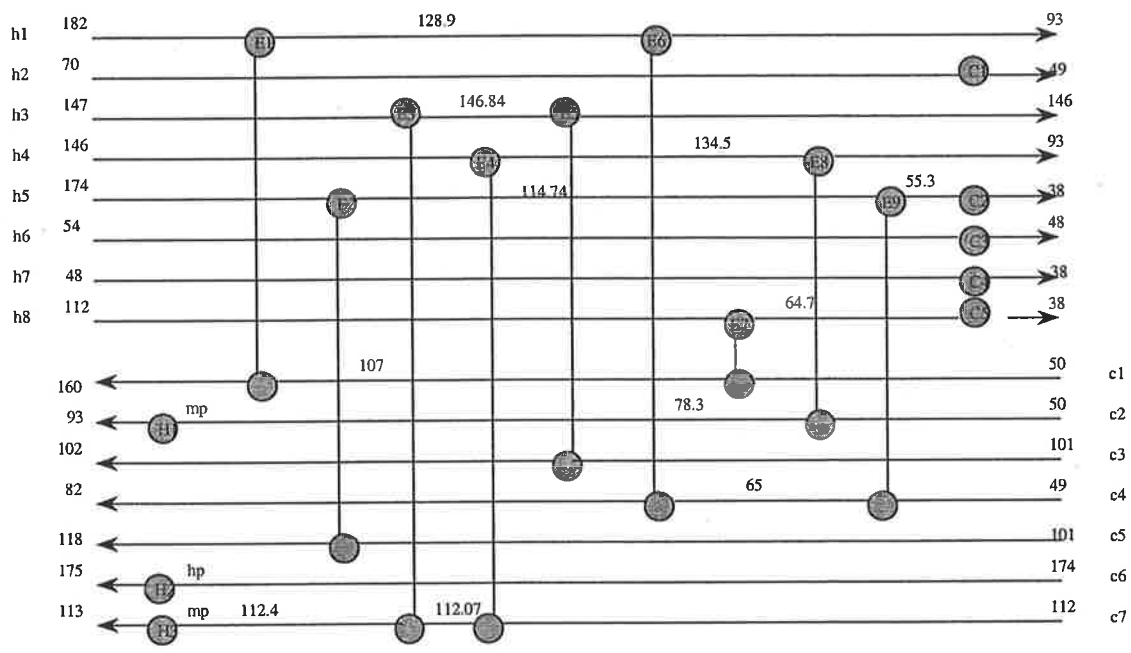


Figure 5.78: The final design using the recursive method

The design provided from Aspen web site is shown in Figure 5.79. The design costs \$6,759,420. In the design, hot steam h3 is used to generate hot utility (mp steam) providing 28.7MW. This provides saving of \$2,644,990. Hence, the design costs \$4,190,680 (This cost does not include the costs which h6, h7 and c6 are heated or cooled by utilities).

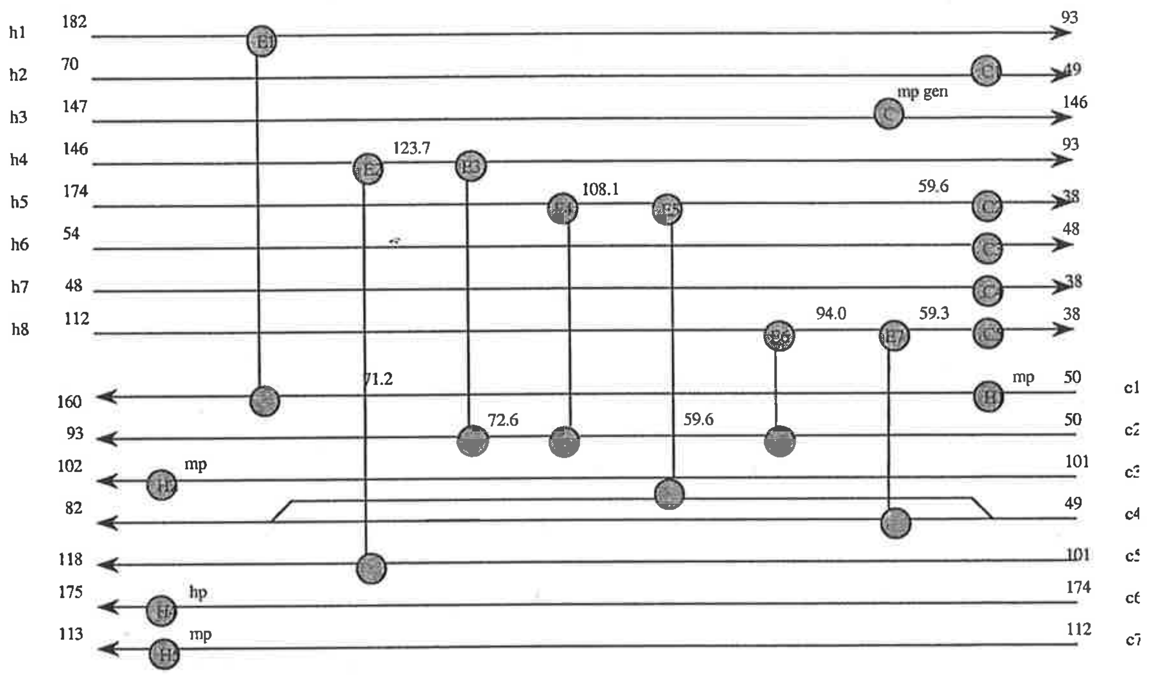


Figure 5.79: Design from Aspen

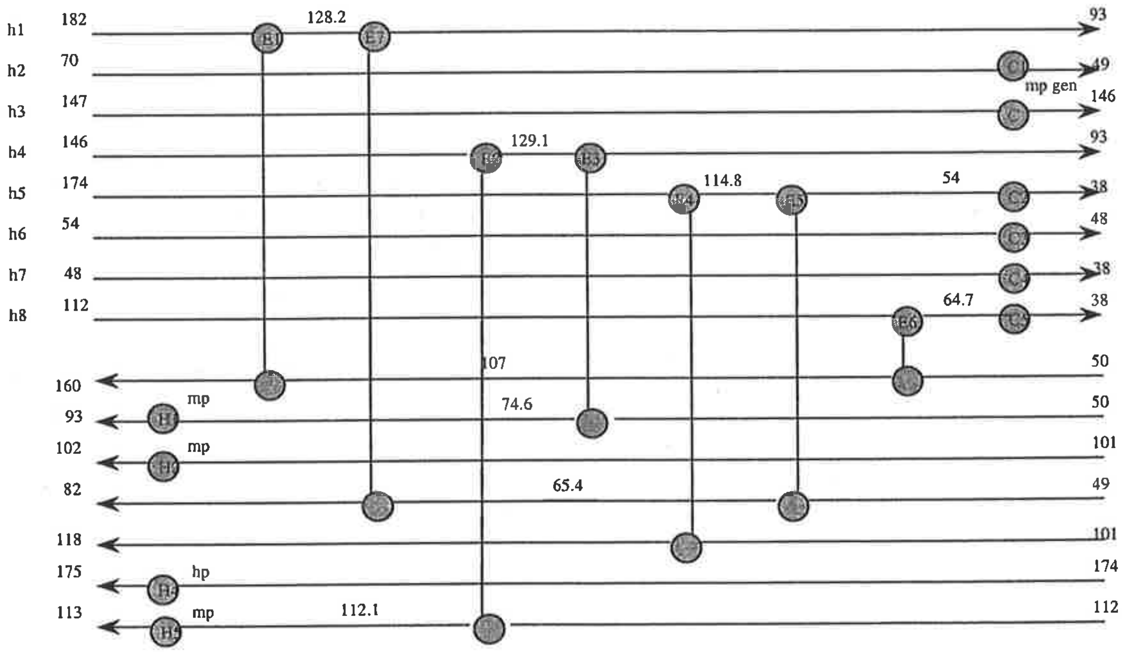


Figure 5.80: Design with constraint

Design with constraints

To provide a comparable design challenge, a constraint is imposed. Hot stream h3 is used to generate hot utility. Following the design procedures, a new design is generated and illustrated in Figure 5.80. This design costs $6,721,400. When compared to the design generated by AspenTech ($6,759,420), the network cost is reduced.

5.6 Conclusions

A new method - called the recursive synthesis method for cost optimal heat exchanger networks, has been proposed. It is based on the combination of a binary tree decomposition, a simple match-selection model and partition temperature optimisation.

Using the new match-selection model, the recursive synthesis method is simple and straightforward. It significantly reduces difficulties and uncertainties associated with the Pinch Design Method. Complex mathematical programming is not required for match selection.

The final optimisation of the partition temperatures is straightforward and the number of variables in each stage is significantly reduced. This optimisation can be performed simply on a spreadsheet without involving complex programming. A series of case studies demonstrates that even without final optimisation, the pre-optimal designs are reasonably good.

The new method can easily cope with the different cost equations, forbidden matches and imposed matches. The design procedure is straightforward and easy to implement.

CHAPTER 6
CONCLUSIONS

Heat exchanger network synthesis is normally a design method involving both heuristic and iterative procedures. Since the design procedures for existing methods are unable to guarantee the design quality, several alternative designs are required. The best design is then chosen from these alternative designs by comparing their costs and structures. Inefficient design procedures may cause exhaustive search techniques for match selection to be quite cumbersome particularly for larger problems.

The general objectives of this research were to discover a synthesis method for heat exchanger network which overcomes difficulties and inefficiencies in the Pinch Design Method. These include uncertainty caused by heuristic rules for match selection, inaccurate trade-offs between capital and operating costs, as well as no systematic design method for parts of streams away from the partition point and so on.

To achieve these objectives, a new synthesis method of heat exchanger networks called the recursive synthesis method has been proposed. In the new method, the system is decomposed into a binary tree. The matches are selected by a match selection model which is developed in this research. The partition temperatures are optimised if they exist. Detailed features of the new method are outlined in the following sections.

6.1 Binary Tree Decomposition

A novel strategy for network decomposition, called binary tree decomposition, is proposed in this work. In the binary tree decomposition, each node may be expanded into two child nodes if decomposition of the node is required.

A new concept, called cost-dominant component analysis is proposed and used to decide whether decomposition of the node is required. It provides an insight into the system rather than simply decomposing the system by physical things, such as temperature intervals. Decomposition for a node will depend on stream data as well as utility costs and capital investment. Generally, if the cost dominant component of a design is capital cost, then decomposition of the node is normally not required. However, if the cost dominant component is energy cost, decomposition may be required except for the case where the design only requires hot or cold utility.

Using the new binary-tree decomposition, the method is capable of solving problems with both significantly different film heat transfer coefficients and equal film heat transfer coefficients. Problems with significantly different film heat transfer coefficients are no longer treated separately. Identical design procedures are applied to all synthesis problems.

6.2 Match Selection Procedures

Based on the proposed simplified superstructure and cost optimal individual matches, a match selection model is developed in this work. This match selection model is a simple integer programming (IP) and can normally be solved without any difficulty.

With this match selection model and match selection procedures, match selection for the design becomes simple and easy to implement. The uncertainty, difficulty and inefficiencies caused by heuristic rules may be avoided. This new match selection procedures means the design depends primarily on the method rather than the designer's experience. Hence, the design quality is improved.

The new match selection procedures also provide a systematic strategy for designing the sections of streams which lie away from the partition temperatures. These sections of streams are called remaining parts and treated as a new problem.

A series of case studies demonstrates that matches selected by these new match selection procedures have constructed reasonable designs for pre-optimal designs. This has also proved that the simplified superstructure is reasonable.

6.3 Optimisation of the Partition Temperatures

Optimisation of the partition temperatures has been shown to provide an efficient procedure to correct for any inaccuracies trade-offs between capital and operating costs. By only optimising the partition temperatures, the number of the variables is significantly reduced. The optimisation is simple and may be simply undertaken by Excel. Because the quality of the pre-optimal design is improved, even without this optimisation procedure, the pre-optimal design may be reasonably close to the optimal design.

6.4 Design for Problem with Constraints

This proposed method readily handles problems with constraints, such as forbidden matches or imposed matches. These can be done by weighting the cost index in the match matrix. If a match is forbidden, the cost index for this particular match is assigned to a value sufficiently large so that the match cannot be selected by the model. By contrast, if a match is imposed, the cost index for the match is assigned to zero and the match will be definitely selected.

6.5 Design with More Detailed Costs

The new proposed method may be easily extended for design using more detailed costing. For example, piping cost, power consumption and valve cost may be taken into account provided that relevant cost laws are available. In fact, these costs are normally considered in industrial design. To do this, we only need to include these cost into the cost index for each individual match.

NOMENCLATURE

a_{ij}	cost index for match between hot stream i and cold stream j
A	heat exchanger area
A_{min}	the minimum total area of heat exchanger network
$Area_{ij}$	area of the heat exchanger
$Area_{ci}$	area of the cooler
$Area_{hj}$	area of the heater
b_h	cost coefficients for heater
b_c	cost coefficients for cooler
b_{ij}	cost coefficients for heat exchanger
B_h	cost coefficients for heater
B_c	cost coefficients for cooler
B_{ij}	cost coefficients for heat exchanger
c_{cu}	fixed charge for cooler
c_{hu}	fixed charge for heater
c_i	cold stream i
c_{ij}	fixed charge for heat exchanger
CCU	cost of cold utility
CHU	cost of hot utility
$Cost_{ij}$	cost index for the stream match
$Cost\_c_{cu}$	cost penalty for not ticking off the hot stream
$Cost\_cpi_{ij}$	capital cost for heat exchanger
$Cost\_h_{hu}$	cost penalty for not ticking off the cold stream
CP	heat capacity flow rate
DFP	Driving Force Plot
DTA	Dual Temperature Approach
EMAT	Exchanger Minimum Approach Temperature

FPDM	Flexible Pinch Design Method
h	film coefficients
HEN	Heat Exchanger Network
HLD	Heat Load Distribution
HRAT	Heat Recovery Approach Temperature
LP	Linear Programming
M_{ij}	match between hot stream i and cold stream j
Mset	a simplified superstructure
Mset'	a simplified superstructure which consists of cost optimal matches
MER	Maximum Energy Recovery
MILP	Mixed Integer Linear Programming
MINLP	Mixed Integer Non Linear Programming
n	plant life time
N_u	the number of the heat exchanger network
N_s	the number of the streams
N_l	the number of the loops
N_p	the number of the independent problems
NLP	Non-Linear Programming
No_h	the number of hot streams
No_c	the number of cold streams
K_{max}	the maximum value of the number of hot stream and cold stream
K_{min}	the minimum value of the number of hot stream and cold stream
PDM	Pinch Design Method
PPDM	Pseudo Pinch Design Method
Q	heat load
Q_{ci}	cold utility used in cooler
Q_{hj}	hot utility used in heater
r	annual interest rate
R	annual recovery factor
RPA	Remaining Problem Analysis
S_{ij}	scaling

$T_{supply,I}$	the supply temperature of hot stream or cold stream i
$T_{target,I}$	the target temperature of hot stream or cold stream i
TI	Temperature Intervals
U	overall heat transfer coefficients
x_{ij}	a binary value (0 or 1)
ΔT_{min}	minimum approach temperature

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