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COST OPTIMUM HEAT EXCHANGER NETWORKS—1. MINIMUM ENERGY AND CAPITAL USING SIMPLE MODELS FOR CAPITAL COST

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Abstract—An important feature of heat exchanger network design is the energy–capital tradeoff. This tradeoff has been regarded as complex due to the number of structural network alternatives usually available, each being subject to continuous optimization.

Current procedures tend to first identify minimum energy networks. The total cost (capital and energy) can then be improved by evolution and continuous optimization. The disadvantages of this approach is that optimality is local to the structures examined. Alternatively, mathematical programming can be used but user interaction with the solution is more complicated and generally performed at higher levels in the problem formulation rather than in the design. Until now no generalized techniques have been introduced for the prediction of global optimum cost networks which allow user interaction with the network structure.

This paper presents a simple methodology for the design of near-optimal heat exchanger networks which systematically takes account of the energy–capital tradeoff. The method is based on setting cost targets, and optimizing these targets prior to design. It is shown how networks can be developed which are typically within 5% of the optimized total cost target. This allows inappropriate design structures to be avoided in design. This part (Part 1) of the paper introduces methods based on simple models for capital cost.

1. INTRODUCTION

A basic feature of heat exchanger networks is the tradeoff between energy and capital cost. In a network such as shown in Fig. 1a the value of the minimum temperature difference (ΔT_{min}) determines the maximum heat recovery and thus the minimum external heating and cooling requirements. As ΔT_{min} increases, demand for utilities increases, but overall heat exchange area decreases (Fig. 1b). The total annual cost is minimized for some value of ΔT_{min} (Fig. 1b).

However, Fig. 1b also shows that the demand for utilities and heat exchange area can often change in a complex way as ΔT_{min} changes. The minimum number of exchangers can also change with ΔT_{min}. Capital cost is affected by network structure as well as exchanger sizes. Thus there is typically a tradeoff observed between network energy consumption, the overall heat exchange area and the number of units (Fig. 1c). Confronted with this complex behaviour, designers generally consider several network alternatives and use continuous optimization on each structure. These continuous optimizations can be difficult to perform in practice. The result is that there is often no certainty of global optimum cost in the final design structure.

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This first article looks at the design of optimum cost heat exchanger networks using simple models for capital cost. As well as developing new procedures, the papers also bring understanding to some previous results by now giving their derivations. In general, the papers develop the ability to predict, locate and design heat exchanger networks which are close to global optimum, while allowing for different levels of detail in the models for capital cost.

2. ESTABLISHED TECHNIQUES FOR HEAT EXCHANGER NETWORK DESIGN

Let us first briefly summarize relevant previous work. Full reviews can be found from Gundersen and Naess (1988) and Nishida *et al.* (1981).

Early methods for the design of heat exchanger networks begin by assuming a value for ΔT_{min} (for example Masso and Rudd, 1969; Ponton and Donaldson, 1974; Linnhoff and Flower, 1978; Linnhoff *et al.*, 1982). This value is usually based on the designer's experience of the energy–capital tradeoff. For a given value of ΔT_{min}, it is possible to predict the minimum utility requirement as a "target" (Hohmann, 1971; Linnhoff and Flower, 1978; Cerda and Westerberg, 1983) and to design networks which achieve this minimum utility (Linnhoff and Hindmarsh, 1983; Papoulias and Grossmann, 1983). Such initial designs are then evolved to correct the energy–capital tradeoff. The usual practice is to relax the ΔT_{min} criterion, introduce or take out units,

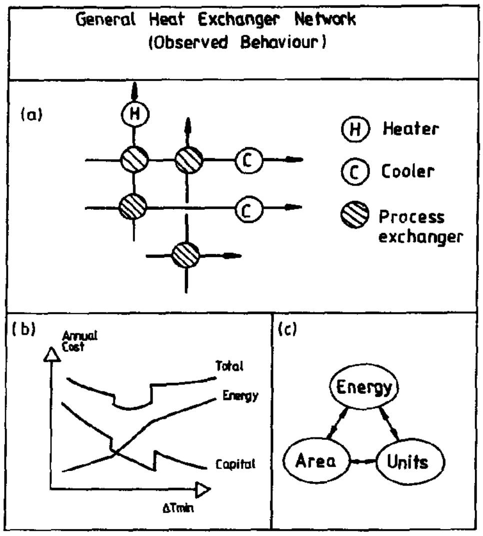


Fig. 1. Observed behaviour for energy–capital tradeoff in heat exchanger networks.

perhaps re-order exchanger sequences, or consider an alternative initial network. Evolution is usually difficult, and doubt often remains as to the optimality of the final design. The problem with this approach is that the minimum capital requirements for the network are not clearly known.

More recently, methods which consider a variation in ΔT_{min} before design have been introduced. Ahmad and Linnhoff (1984) suggested the principle of ΔT_{min} optimization ahead of design based on targets for energy and capital. No detailed algorithms were presented. When Saboo *et al.* (1986) presented network design methods based on linear programming they also suggested that ΔT_{min} should be varied in an outer loop of the inner loop design program to obtain the optimum network. Although ΔT_{min} was not optimized before design, the purpose was nevertheless to balance the energy–capital tradeoff.

This present paper continues from the suggestion of Ahmad and Linnhoff (1984) that ΔT_{min} should be optimized ahead of design by giving specific capital targeting and design procedures which are based on thermodynamic principles.

3. PRINCIPLES FOR MINIMUM AREA

Area is important in determining network capital (Ahmad, 1985). We now develop principles for minimum area in heat exchanger networks.

3.1. Hohmann's model for minimum area

Start by considering the example in Fig. 2a, where two hot streams exchange heat against a single cold stream. If we assume the overall heat transfer coefficient U is constant for all exchangers and these exchangers are countercurrent units then the network has an area of 88 m^2.

Figure 2b shows a different network with stream-splitting. Its area is 84 m^2. The reason is that it has better countercurrent behaviour in terms of the overall network. In Fig. 2a the matches are in temperature sequence whereas in Fig. 2b the matches share more of the available temperature differences by splitting the cold stream.

Figure 2c shows that we can do better still. The network area is now 77 m^2. This is the minimum area for the stream set as defined. The network has been developed by stream-splitting only where streams compete for the same driving forces by overlap in temperature (Hohmann, 1971).

When the *overall* heat exchange is truly countercurrent, minimum total area is achieved if U = constant (Nishimura, 1980). Thus, Hohmann's model shows how to construct networks achieving overall countercurrent heat exchange. However, the implied splitting configuration can become very complex for several hot and several cold streams. Indeed, Hohmann does not explain the method for such cases. Also, the model does not allow for the different U-values which occur in practice.

3.2. An alternative technique for minimum area

Staying with our example from Fig. 2, the data are shown in terms of the composite curves in Fig. 3. Overall countercurrent heat exchange now appears as vertical heat transfer on the composite curves. Partitioning of the stream data to follow the temperatures of the vertical model then leads to the minimum area design for this example.

In Fig. 4 a general way is introduced in which vertical heat transfer can be ensured. First, the composite curves are divided into vertical "enthalpy intervals" (Fig. 4a). The intervals are defined wherever a change in slope occurs in either composite profile. Next, a network design is considered within each enthalpy interval which can satisfy vertical heat transfer. Figure 4b demonstrates this for an interval which contains two hot streams and three cold streams. Each hot stream is split into the same number of branches as the number of cold streams in that interval. Similarly, each cold stream is split into the same number of branches as the number of hot streams in that interval. Hence, each hot stream can be matched with each cold stream such that every match occurs between the corner temperatures of the enthalpy interval. The heat exchange of these matches must therefore appear as vertical on the composite curves.

We note that $n_H \cdot n_C$ number of matches are implied in each enthalpy interval by this construction, where n_H (n_C) is the number of hot (cold) streams in the interval. Generally, however, a minimum of $n_H + n_C - 1$ matches are required for vertical heat transfer in each such interval as discussed by Ahmad and Smith (1989). In fact various possibilities exist for designing networks which satisfy the vertical model, but for the purposes of the present paper it is

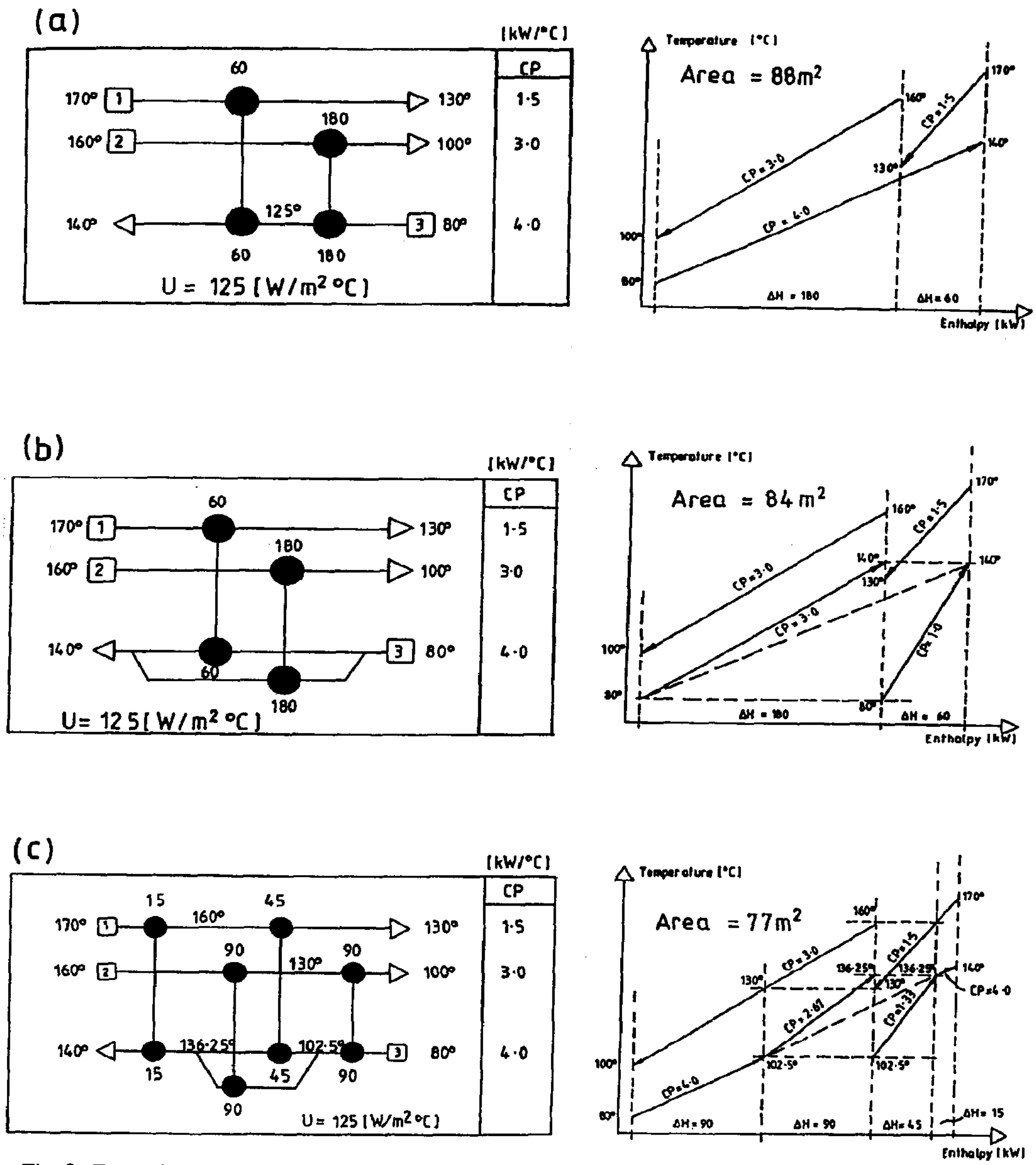


Fig. 2. Example: (a) network with exchangers in temperature sequence on cold stream; (b) network with exchangers sharing temperature span of cold stream; and (c) network with exchangers showing correct distribution of temperatures for minimum area.

sufficient to continue using the network model having $n_H \cdot n_C$ matches in each interval as illustrated in Fig. 4b.

The minimum total area could be taken as the sum of the areas of all such exchangers from all enthalpy intervals. However, this is not necessary if U = constant. From the composite curves, the area from vertical heat transfer in interval i is simply:

$$A_i = \Delta H_i/(U \cdot \Delta T_{LM \cdot i}), \tag{1}$$

where ΔH_i is the enthalpy width of interval i and $\Delta T_{LM \cdot i}$ is the logarithmic mean temperature difference of interval i.

Hence, the total minimum network area is given by:

$$A_{min} = (1/U) \sum_{i}^{\text{intervals}} (\Delta H_i/\Delta T_{LM \cdot i}). \tag{2}$$

This shows that in order to derive an area target based on U = constant no design is required.

3.3. *Different heat transfer coefficients in the model for minimum area*

We will now develop this method to allow for different U-values. Consider again the design in

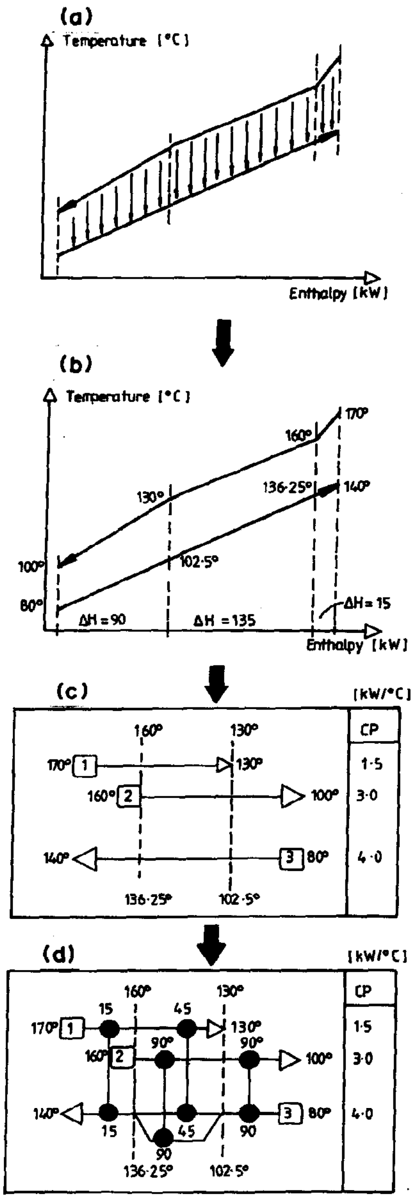


Fig. 3. Example: resolving temperature contention using the composite curves: (a) overall countercurrent heat exchange appears as vertical heat transfer on the composites; (b) the temperatures of enthalpy intervals show where stream-splitting will be required; (c) these temperatures can be marked on the grid; and (d) used to guide design for temperature contention.

Fig. 4 for vertical heat transfer in enthalpy interval i of the composite curves. If the heat transfer coefficients differ then the total area of these exchangers is:

$$A_i = (1/\Delta T_{LM\cdot i})[Q_{13}/U_{13} + Q_{14}/U_{14} + Q_{15}/U_{15} + Q_{23}/U_{23} + Q_{24}/U_{24} + Q_{25}/U_{25}] \quad (3)$$

where Q_{13} is the duty of the match between streams 1 and 3, U_{13} its overall heat transfer coefficient, etc.

Now,

$$1/U_{13} = 1/h_1 + 1/h_3,$$
$$1/U_{14} = 1/h_1 + 1/h_4,$$
$$1/U_{15} = 1/h_1 + 1/h_5,$$
$$1/U_{23} = 1/h_2 + 1/h_3,$$
$$1/U_{24} = 1/h_2 + 1/h_4,$$
$$1/U_{25} = 1/h_2 + 1/h_5, \quad (4)$$

where h_1 is the heat transfer coefficient of stream 1 (including film, wall and fouling resistances), etc.

So,

$$A_i = (1/\Delta T_{LM\cdot i})[(1/h_1)(Q_{13} + Q_{14} + Q_{15}) + (1/h_2)(Q_{23} + Q_{24} + Q_{25}) + (1/h_3)(Q_{13} + Q_{23}) + (1/h_4)(Q_{14} + Q_{24}) + (1/h_5)(Q_{15} + Q_{25})]. \quad (5)$$

But,

$$Q_{13} + Q_{14} + Q_{15} = (q_1)_i,$$
$$Q_{23} + Q_{24} + Q_{25} = (q_2)_i,$$
$$Q_{13} + Q_{23} = (q_3)_i,$$
$$Q_{14} + Q_{24} = (q_4)_i,$$
$$Q_{15} + Q_{25} = (q_5)_i, \quad (6)$$

where $(q_j)_i$ is the enthalpy change of stream j in enthalpy interval i.

So,

$$A_i = (1/\Delta T_{LM\cdot i})[(q_1)_i/h_1 + (q_2)_i/h_2 + (q_3)_i/h_3 + (q_4)_i/h_4 + (q_5)_i/h_5]. \quad (7)$$

The argument applies in general for other enthalpy intervals. Summing up over all intervals on the composite curves gives:

$$A_{min} = \sum_i^{\text{intervals}} (1/\Delta T_{LM\cdot i}) \sum_j^{\text{streams}} (q_j/h_j)_i. \quad (8)$$

This simple formula incorporates stream individual heat transfer coefficients and allows a "target" for the minimum heat exchange area to be calculated from the composite curves. This result has been presented previously without proof or explanation by Townsend and Linnhoff (1984).

Let us consider whether vertical heat transfer is strictly correct for minimum area when h-values are not all identical. Figure 5 shows two gas streams (low h-value) and two liquid streams (high h-value). Vertical heat transfer between the composites gives a design of 1616 m^2. The non-vertical or "criss-crossed" arrangement requires only 1250 m^2. To understand this, we distinguish three effects in heat transfer which

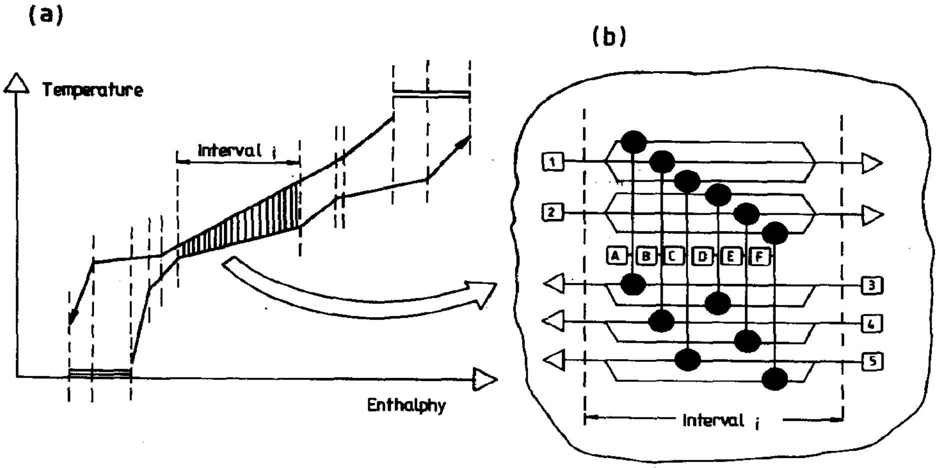


Fig. 4. Example of general stream-splitting and matching scheme for vertical heat transfer in an enthalpy interval of the composite curves.

occur due to the different coefficients:

(i) *resistance to heat flow*—lower h-values means the need for more heat exchange area and vice versa;

(ii) *differences between coefficients*—lower overall area may be achieved by giving more of the available temperature differences to streams with lower h-values;

(iii) *isolation of low h-values*—because resistances in heat exchange operate in parallel, lower overall area may be achieved if streams with low h-values are matched with each other.

The targeting formula in equation (8) accounts for effect (i) but not effects (ii) and (iii). In practice, as will be discussed in Part 2 of this paper (Ahmad *et al.*, 1990), effect (i) is more significant than effects (ii) and (iii) in determining the minimum area requirement for a set of streams. The discrepancy in area target due to effects (ii) and (iii) is usually less than 10% of the total area (Townsend and Linnhoff, 1984; Ahmad, 1985; Townsend, 1989). The "vertical heat transfer" targeting formula will continue to be used in Part 1 of this paper for targeting purposes. More complex methods to take account of

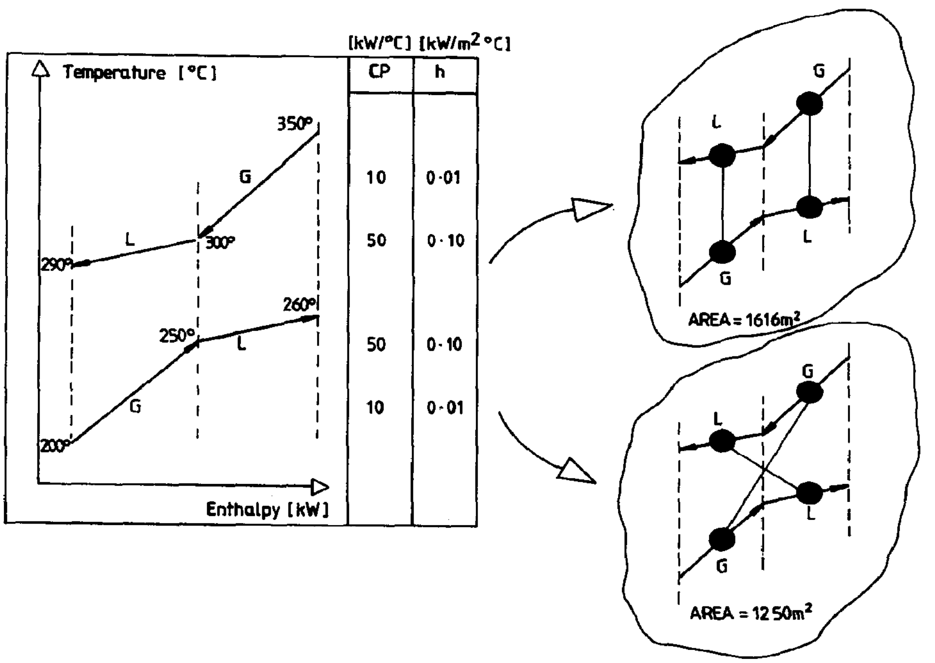


Fig. 5. Heat transfer between streams of very different heat transfer coefficients. Vertical heat exchange can lead to greater overall area than a criss-crossed arrangement.

effects (ii) and (iii) are considered in Part 2 of the paper.

4. DESIGN FOR MINIMUM AREA

The Pinch Design Method (Linnhoff and Hindmarsh, 1983) leads to networks which meet the energy target. An extension to the method is now proposed which also allows approach to the area target to within 10% or better. This is done using minimum (or near minimum) number of units while satisfying minimum energy. In practice we will not try to design for exactly vertical heat transfer since this would result in designs which are too complex to be practical both in terms of excessive numbers of units and excessive stream splits. Instead, verticality is approached as closely as possible with the minimum (or near minimum) number of units and stream splits. In other words a small sacrifice in area will be allowed in order to gain a great simplification in network structure whilst still achieving the energy target.

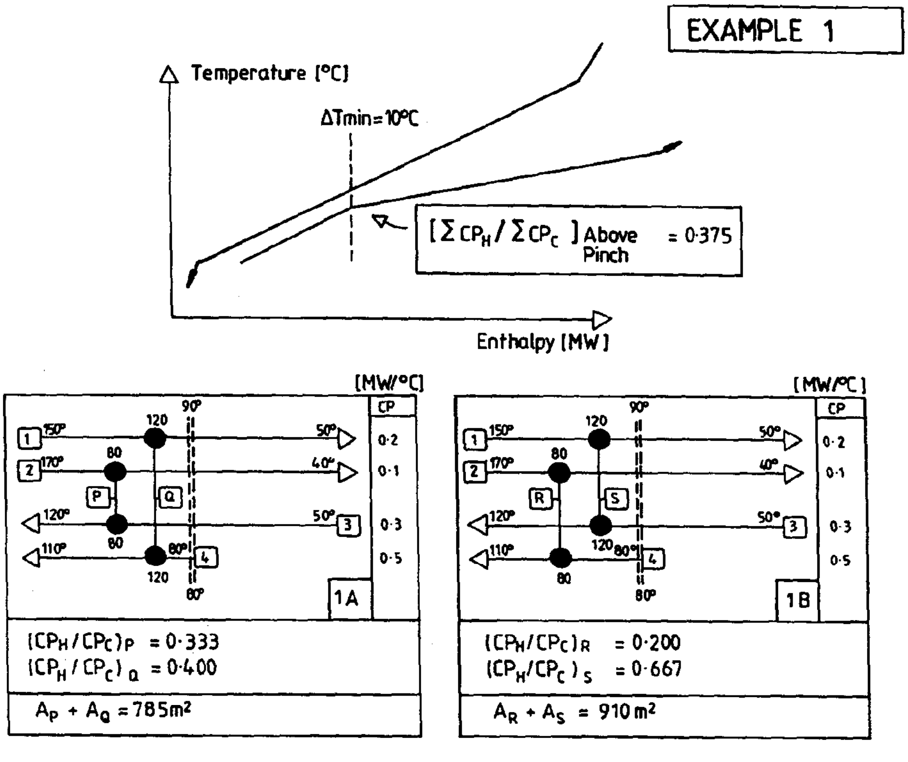
This section introduces three techniques in increasing order of sophistication. If the area target is not sufficiently approached with one method the next is used, and so on.

4.1. The CP-rules

The Pinch Design Method requires $CP_{IN} \leqslant CP_{OUT}$ for observing ΔT_{min} in pinch matches (Linnhoff and Hindmarsh, 1983). This rule is also compatible with approaching minimum area in the pinch region, where most of the network area is often concentrated.

The *CP*-rules ensure that the temperature profiles in exchangers situated at the pinch diverge away from the pinch. The composite curves also diverge away from the pinch. The *CP*-rules thus ensure that individual exchangers tend to follow the temperature profile of the composite curves. In fact, if pinch matches have *CP*-ratios identical to that of the composites, the matches have exactly vertical heat transfer. The design relationship for approaching minimum area around the pinch can therefore be expressed more precisely:

$$\left(\frac{CP_H}{CP_C}\right)_{\text{pinch match 1}} \simeq \left(\frac{CP_H}{CP_C}\right)_{\text{pinch match 2}} \simeq \cdots \simeq \left(\frac{CP_{\text{hot composite}}}{CP_{\text{cold composite}}}\right)_{\text{pinch}}. \quad (9)$$



U = 100 [W/m²°C] all matches

Utilities: Saturated Steam: 180°C; Cooling Water: 20°C-40°C

Fig. 6. Example 1: the *CP*-ratio of the composite curves at the pinch is more closely approached by network 1A than network 1B.

Example 1 in Fig. 6 shows two different topologies for a stream set above the pinch. Both networks obey the CP-inequalities as far as basic feasibility is concerned. However, network 1A has pinch matches with CP-ratios closer to that of the composites and obtains a lower area than network 1B.

4.2. The Driving Force Plot

Consider now Example 2 in Fig. 7. Both networks have the same CP-ratios for pinch matches. However, network 2A comes to within 16% of the above pinch area target, while network 2B requires 108% more area than target. Why is there such a large discrepancy? Obviously the CP-rules are not adequate here. Examining the composite curves, we suspect network 2B makes poor use of driving forces away from the pinch. To take this further we use the concept of the "Driving Force Plot". This plot was introduced by Linnhoff and Vredeveld (1984) without any detailed explanation or procedures.

The area target is based on the vertical temperature differences along the *whole* composite curves. Ideally, we need to measure the temperature differences of individual matches against the vertical driving forces available on the composites. A simple way of expressing this is firstly to draw the vertical temperature difference ΔT between the composites as it changes with the temperature of say the cold composite T_{cold} (Fig. 8a). Equivalently, $\Delta T = f(T_{hot})$ or $T_{hot} = f(T_{cold})$ may also be used. The diagram is called the "Driving Force Plot" (Fig. 8a).

Next, individual matches are shown in these coordinates (Fig. 8b). Matches displaying vertical heat transfer on the composites fit the Driving Force Plot exactly, such as the match shown in Fig. 8b. Matches which are not vertical (or which criss-cross) on the composites show a blatant misfit (Fig. 8c, d). Matches using excessive temperature differences have less area than if they had been vertical, but cause other (subsequently placed) matches to have smaller temperature differences. The net result overall is increased heat exchange area for the network.

The Driving Force Plot provides a rapid and easy to use guideline for designing networks which are close to minimum area. However, it is only a

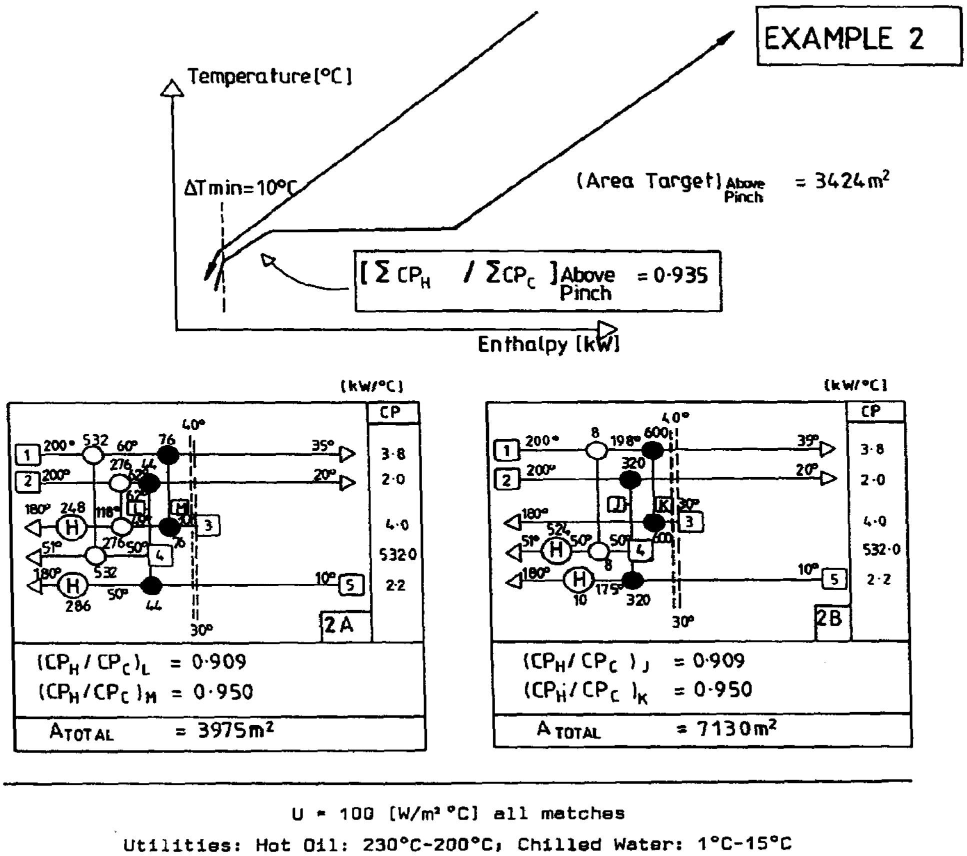


Fig. 7. Example 2: both networks have identical CP-ratios for pinch matches and these are close to the CP-ratio of the composite curves at the pinch. There is, however, significant difference in network areas.

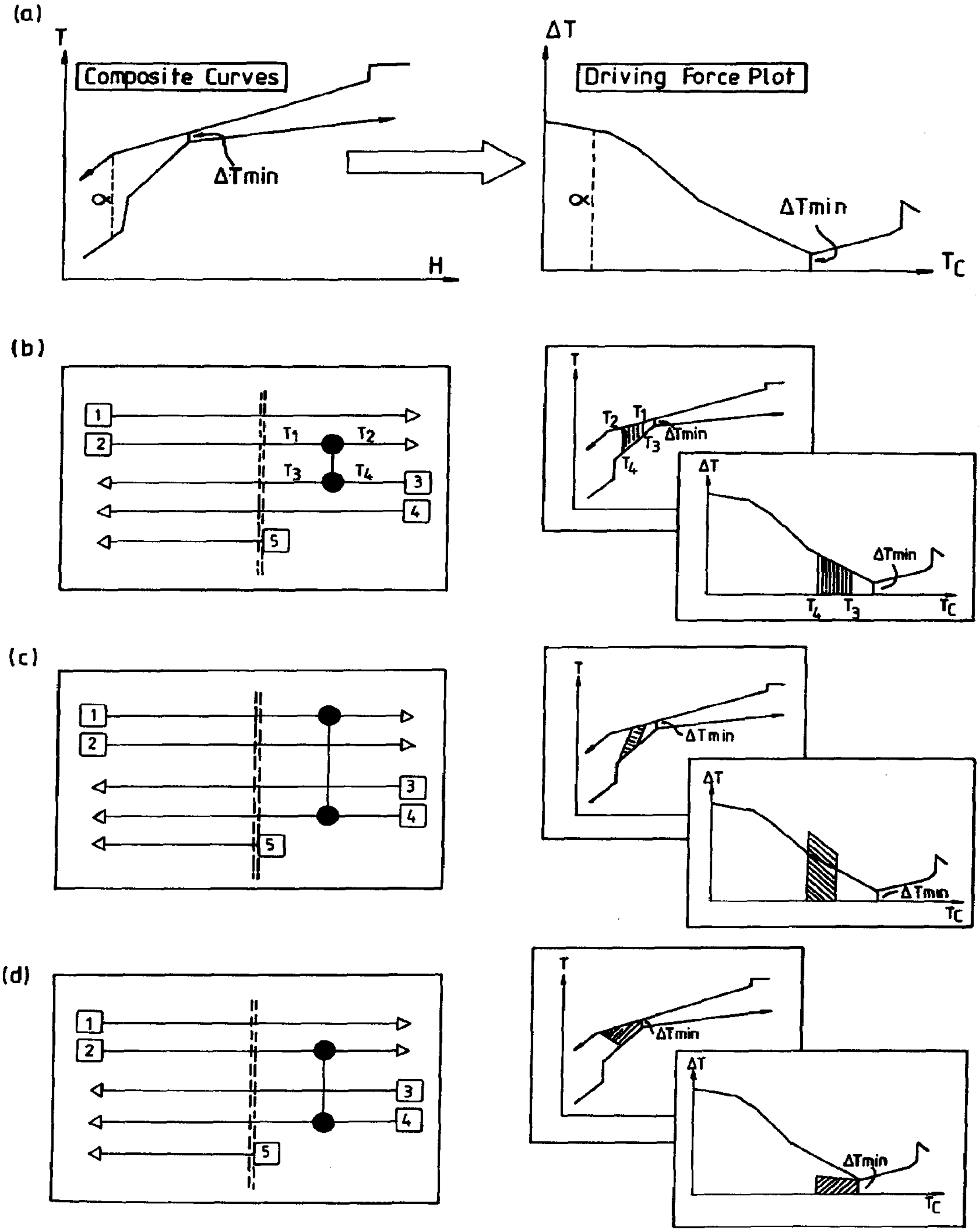


Fig. 8. The Driving Force Plot: (a) construction from the composite curves; (b) match with "vertical" heat transfer; (c) match using excessive driving force; and (d) match under-utilizing driving force.

guideline and does not provide quantitative information.

Networks 2A and 2B are displayed against their Driving Force Plot in Fig. 9. The pinch matches placed according to the CP-rules follow well the slope of the Driving Force Plot near the pinch. Away from the pinch, however, network 2B shows a poorer overall fit to the plot. Its pinch matches are too large in duty and under-utilize driving forces away from the pinch. These duties were established using the "tick-off" heuristic (Linnhoff and Hindmarsh, 1983) for obtaining minimum number of units in the design.

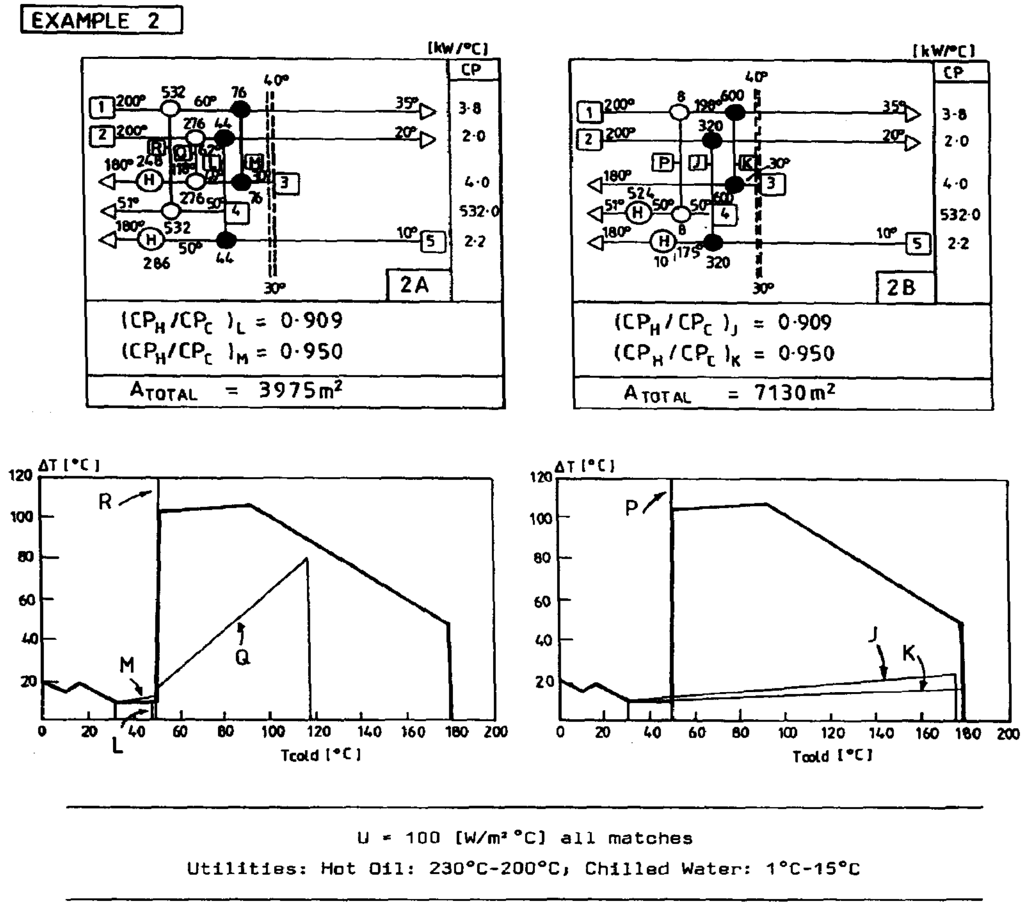


Fig. 9. Example 2 re-examined: networks 2A and 2B compared on the Driving Force Plot. Network 2B shows a much poorer overall fit to the plot than network 2A.

The plot shows the tick-off heuristic is inappropriate here for achieving low network area. Violation of the tick-off rule usually means additional units above target, as in network 2A. The significantly improved area performance in this example gives lower overall capital cost. Designs achieving a good fit to the Driving Force Plot in minimum number of units or within 10% of this (to the nearest integer number of units) are usually within 10% of the area target (Ahmad, 1985).

4.3. Remaining Problem Analysis

Suppose a design obtains a good fit to the Driving Force Plot but the final network area is appreciably above target. Such an occurrence is infrequent considering the plot steers design towards vertical heat transfer and minimum area. Figure 10, however, demonstrates the plot may not always be sufficient for minimum area. Networks 3A and 3B appear remarkably similar in use of driving forces, but 3B has an area 22% in excess of the above-pinch target whereas 3A is only 10% above this target.

The Driving Force Plot works in temperatures only, neglecting the effect of duty on heat exchange area. It is possible for matches to appear identical in Driving Force coordinates, yet have very different duties. Generally, good utilization of driving forces for matches of large duty is required in regions of small temperature difference.

We therefore need quantitative assessment of fit to the Driving Force Plot, or rather approach to the area target, during design development. One such tool is "Remaining Problem Analysis", explained in Fig. 11. Suppose the minimum total area possible for a design completed *after* accepting a match M is $A_{total \cdot M}$. This is the sum of the match area a_M and the area target for the remaining stream data $A_{r \cdot M}$. Subtraction of the original area target for the whole stream data A_{min} gives the minimum area penalty incurred.

The analysis can quantify both surplus and deficit use of driving forces. A large ΔT match incurs area penalty from the small ΔT caused in the remaining problem. A small ΔT match incurs area penalty from the match itself.

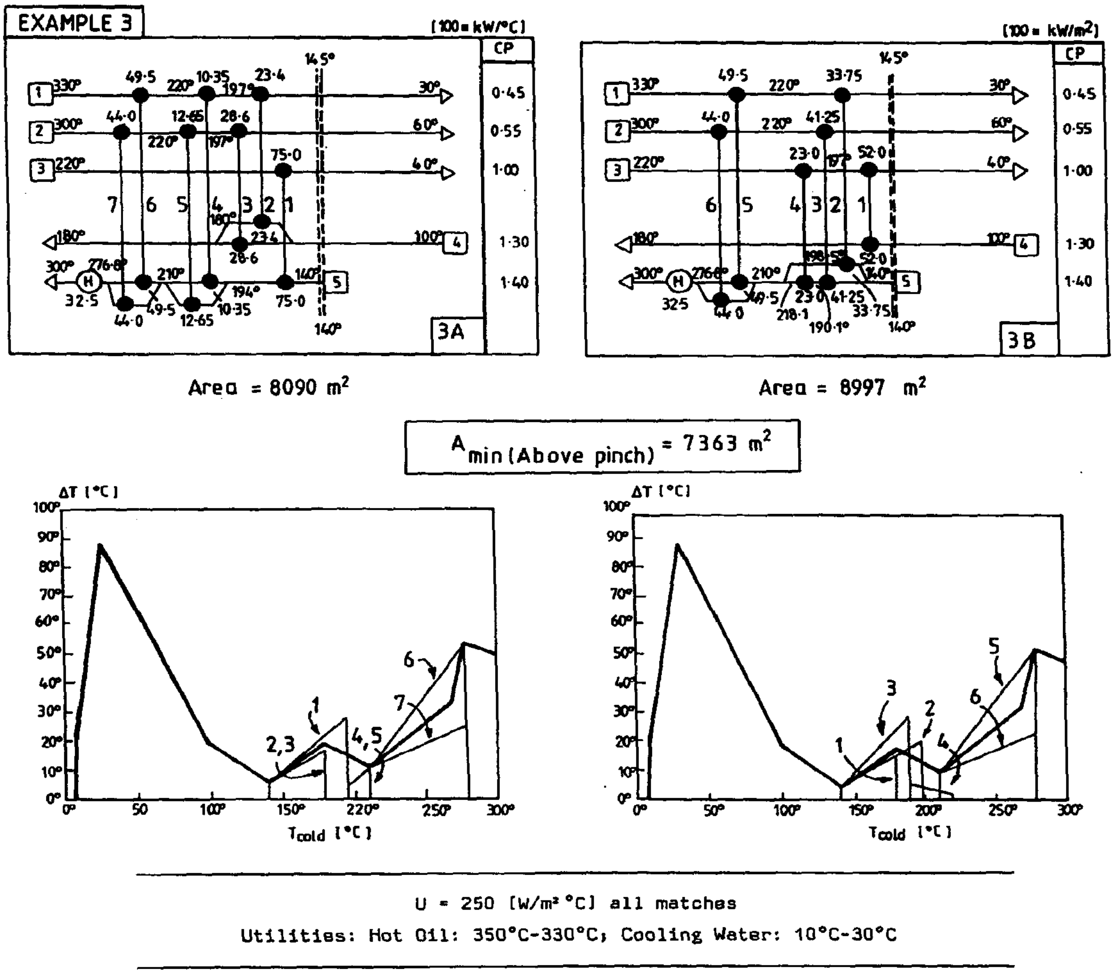


Fig. 10. Example 3: both networks show very similar fit to the Driving Force Plot but differ appreciably in area.

The Remaining Problem Analyses for networks 3A and 3B are shown in Fig. 12. It is now clear that match 4 in network 3B is not as good as the rest. Surprisingly, it looks similar on the Driving Force Plot (Fig. 10) to matches 4 and 5 in network 3A, which return much lower area penalties. The Remaining Problem Analysis improves on the Driving Force Plot. At present, it is the only known method for quantifying approach to the targets *during* design development.

The Remaining Problem Analysis discussed so far treats each match in isolation of the others when several matches exist at any stage of design (as in Fig. 12). In other words, the remaining problem is defined as the full stream data excluding only the hot and cold stream sections of the match being analyzed. Rather than using this individual match basis the analysis can instead be performed on a cumulative basis by considering the total area of all matches so far placed in the design and defining the remaining problem to be only the stream data awaiting matches. The total area predicted after match M is now:

$$A'_{\text{total}\cdot M} = \left(\sum_{i=1}^{M} a_i\right) + A'_{r\cdot M} \qquad (10)$$

($A'_{\text{total}\cdot M}$ and $A'_{r\cdot M}$ are similar to $A_{\text{total}\cdot M}$ and $A_{r\cdot M}$ except that the prime denotes the remaining problem is now defined differently). This method has the advantage of reporting the progress of all the matches together in the design up to that point. Its disadvantage is that the area penalty associated with a match depends on its sequence. That is, which other matches have been placed beforehand in the design. In general, if during design the area penalty obtained on the cumulative match basis remains within 10% of the area target then the influence of sequencing on individual match penalties is small and can be ignored. In the unlikely case where a design with a larger penalty is indeed to be completed then the individual match area penalties should also be

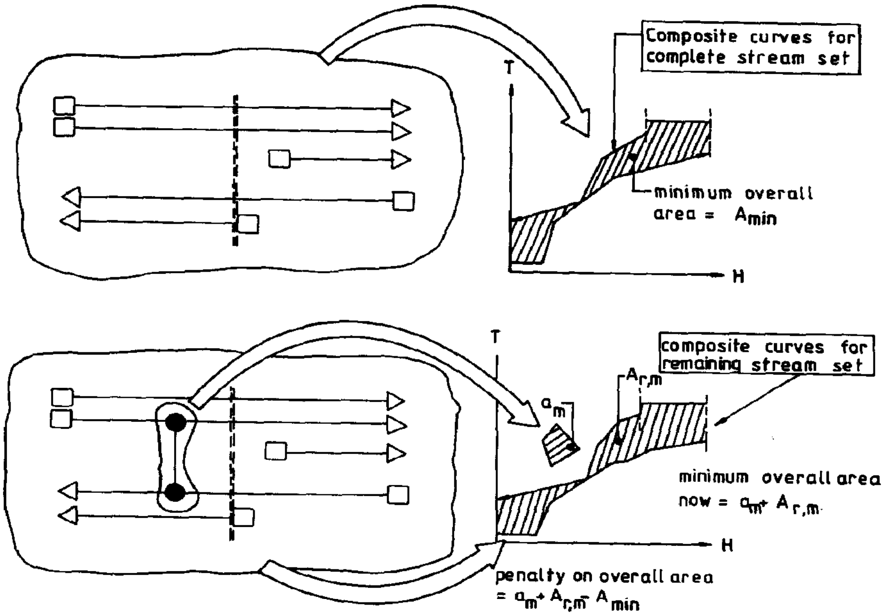
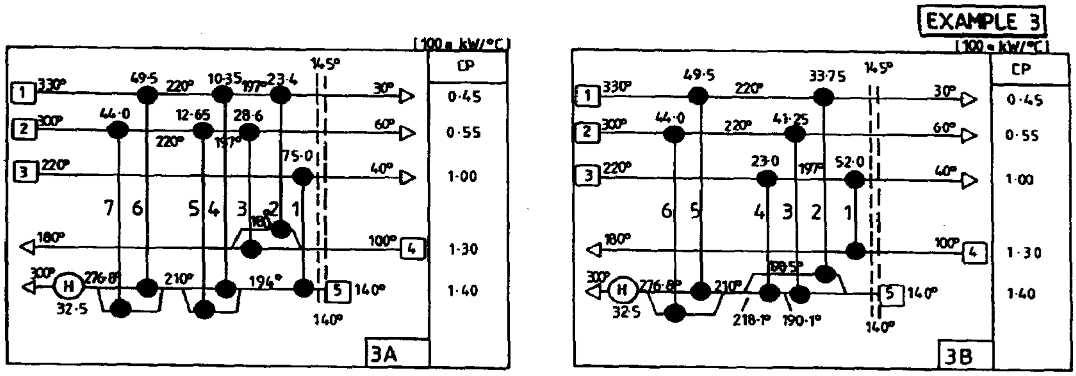


Fig. 11. Remaining Problem Analysis for area.



A_{min} (Above Pinch)	= 7363 m²	= 100·0%
Match 1 : $A_{TOTAL,1}$		= 106·1%
Match 2 : $A_{TOTAL,2}$		= 100·0%
Match 3 : $A_{TOTAL,3}$		= 100·1%
Match 4 : $A_{TOTAL,4}$		= 102·3%
Match 5 : $A_{TOTAL,5}$		= 102·9%
Match 6 : $A_{TOTAL,6}$		= 100·9%
Match 7 : $A_{TOTAL,7}$		= 100·9%

A_{min} (Above Pinch)	= 7363 m²	= 100·0%
Match 1 : $A_{TOTAL,1}$		= 100·1 %
Match 2 : $A_{TOTAL,2}$		= 100·9%
Match 3 : $A_{TOTAL,3}$		= 102·5%
Match 4 : $A_{TOTAL,4}$		= 111·1%
Match 5 : $A_{TOTAL,5}$		= 100·9%
Match 6 : $A_{TOTAL,6}$		= 100·9%

U = 250 [W/m² °C] all matches

Utilities: Hot Oil: 350°C-330°C, Cooling Water: 10°C-30°C

Fig. 12. Example 3 re-examined; the Remaining Problem Analysis for match 4 in network 3B shows significant penalty in area for the network.

evaluated for subsequent matches to isolate the error due to the chosen sequence.

While Remaining Problem Analysis has already been suggested as a tool for designing for minimum energy (Linnhoff and Hindmarsh, 1983), it is seldom used for that purpose. This is because minimum energy is virtually guaranteed by obeying the pinch division in design. With minimum area, however, the situation is quite different. We are seeking only to *approach* the area target by using near minimum number of matches. Remaining Problem Analysis for area may need to be used frequently during design to ensure that a satisfactory network area results.

4.4. Understanding the design

The use of the Driving Force Plot and Remaining Problem Analysis represents an important change in design philosophy and understanding compared with previous network synthesis techniques.

Firstly, the misuse of driving forces always leads to an area penalty above the target, but not necessarily to an energy penalty. However, if too large a driving force is used at any stage in the design then an energy penalty can result. This is because the remaining problem can become infeasible in temperature difference (or violate ΔT_{min}) unless its energy consumption is increased above target. In other words, an extreme violation of the area target can manifest itself as a violation of the energy target.

Secondly, violation of ΔT_{min} or any of the targets may occur because there exist forbidden or preferred match options. These often result from safety, operability and layout considerations in the design. The techniques presented here cannot account for the effects of forbidden matches: methods for targeting and design in such cases have been presented by Cerda and Westerberg (1983), Papoulias and Grossmann (1983) and O'Young (1989). However, for preferred or imposed matches the designer can assess the target violations by using the Remaining Problem Analysis, to decide how compatible the preferred network structure is with obtaining a near optimum design. This ability to accept or reject options in the design subject to the match evaluations stresses the importance of user interaction during network development and the on-going use of targets in the design.

4.5. Procedure to design for minimum energy and capital

Figure 13 summarizes the targeting and design procedure developed so far. For a given value of ΔT_{min}, the composite curves, pinch location, energy, units and area targets are found. A network can be designed using the CP-rules of the Pinch Design Method.

The resulting area of the design may be poor in relation to the area target due to poor design away from the pinch. If this is the case then the network can be modified (or redesigned) with additional use of

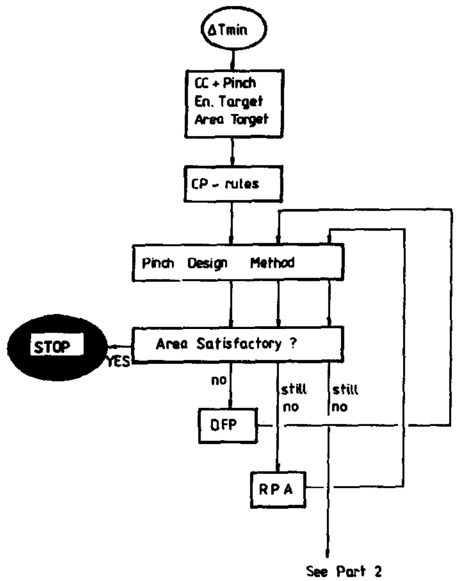


Fig. 13. Procedure to design for minimum energy and capital (for a given value of ΔT_{min}).

the Driving Force Plot or Remaining Problem Analysis. Whichever route is chosen, design is usually steered towards minimum (or near-minimum) number of units.

In cases where network designs require more detailed models of capital cost approach to vertical heat transfer and the Driving Force Plot becomes less useful (see Part 2 of this paper). Remaining Problem Analysis, however, can still be applied if used in conjunction with the more sophisticated targeting models for network area and capital cost as discussed in Part 2.

5. COMBINING ENERGY AND AREA TARGETS

Energy and area targets can be evaluated over a range of ΔT_{min} values (Fig. 14a). This section discusses how the target profiles relate, how they combine for total network cost, and how ΔT_{min} is optimized before design.

5.1. Topology criss-crossing

Plotting the targets for energy and area together generates the plot shown in Fig. 14b. Some useful physical observations can be made on this diagram. The curve represents a guide to the limit of feasible designs. Most network designs will exist close to the line or above it. However, some designs can perform marginally better than target due to the simplifying assumptions used in the simple area targeting formula. Hence a design may be slightly below the line. Any network actually on the line achieves the area target for its energy consumption. It therefore exhibits vertical heat transfer. The global optimum

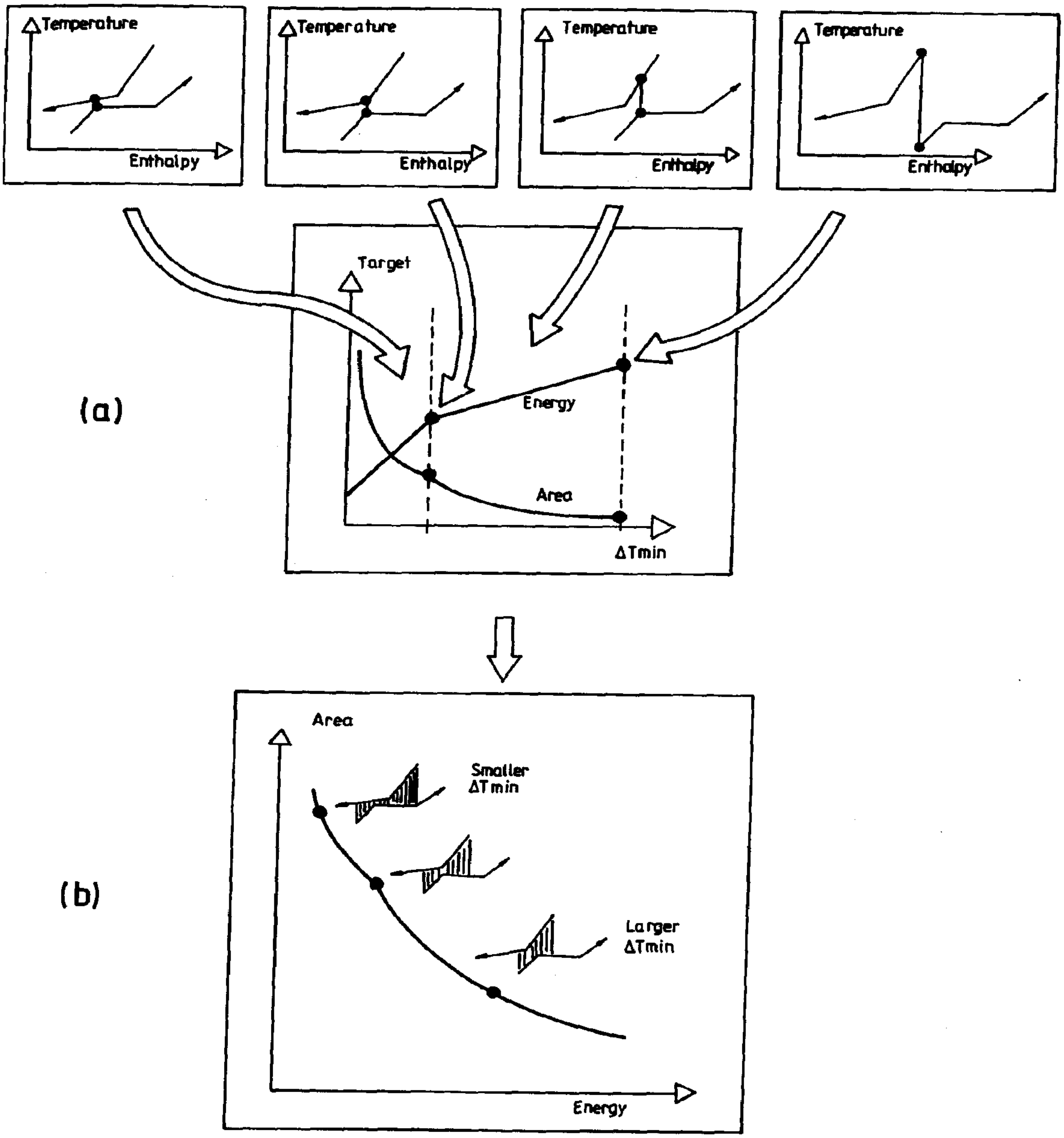


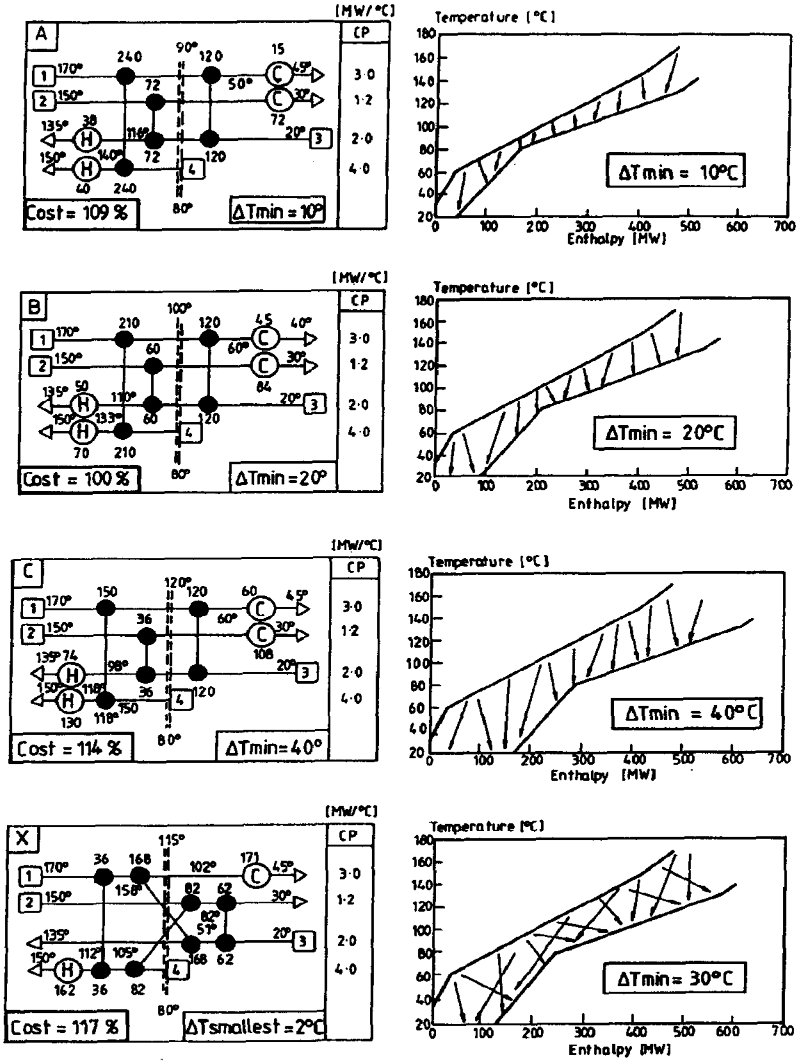
Fig. 14. Targets can be evaluated over a range of ΔT_{min} values to give profiles for minimum energy and area.

cost network lies at some point near the line corresponding with the optimum ΔT_{min}.

These features are demonstrated by the example in Fig. 15. Networks A, B and C are designed at $\Delta T_{min} = 10$, 20 and 40°C, respectively for the example stream set. They have identical structures and all display almost vertical heat transfer. The cheapest total cost is for network B.

Now observe network X, corresponding with the energy target for $\Delta T_{min} = 30$°C, but grossly violating this ΔT_{min} value, having a smallest ΔT of 2°C in the design. It has a different structure and its heat transfer appears significantly criss-crossed on the composite curves. Its total cost is greater than the others.

Figure 16 shows the location of these designs on the Energy–Area Plot. Networks close to the line (A, B and C) have near-minimum area for their energy. They have topologies which lead to near-vertical heat transfer. Network X lies far from the line and does not follow this pattern. The chosen topology has led to severe criss-crossing. The correct energy–capital tradeoff is found somewhere near the target line. In this example, it occurs in the vicinity of network B.



U = 25 [W/m² °C] all matches

Utilities: Hot Oil: 230°C–200°C; Chilled Water: 1°C–15°C

Costs: Exchanger Capital Cost [$] = 400 * Area [m²]
Plant Lifetime = 5.0 [years]; Rate of Interest = 0.0 [%]
Hot Oil: 60000 [$/MW.year]
Chilled Water: 6000 [$/MW.year]

Fig. 15. Example to show a network structure featuring near-vertical heat transfer at $\Delta T_{min} = 10$, 20 and 40°C and a different structure featuring significant criss-crossing at $\Delta T_{min} = 30$°C.

5.2. Criss-crossing and cross-pinching

To achieve the energy target without violating ΔT_{min} requires no cross-pinch heat transfer. To achieve the area target of equation (8) requires no criss-cross heat transfer. Are the two principles related?

1. Consider again vertical heat transfer on the composite curves (Fig. 17a). In the region of the pinch, to avoid transferring heat across the pinch, the heat transfer must be vertical. Conversely, cross-pinch heat transfer is criss-crossed. These two important principles are therefore compatible: achieving the energy target without violating ΔT_{min} is necessary (but not sufficient) to achieve the area target of equation (8).

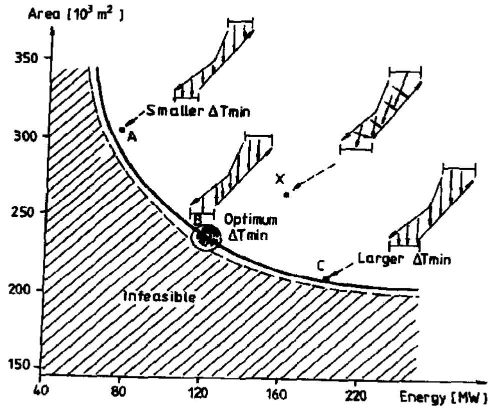


Fig. 16. Networks located on the Energy–Area Plot. Designs with near-vertical heat transfer are close to the target line. A design with criss-crossed heat transfer is further away from the target line.

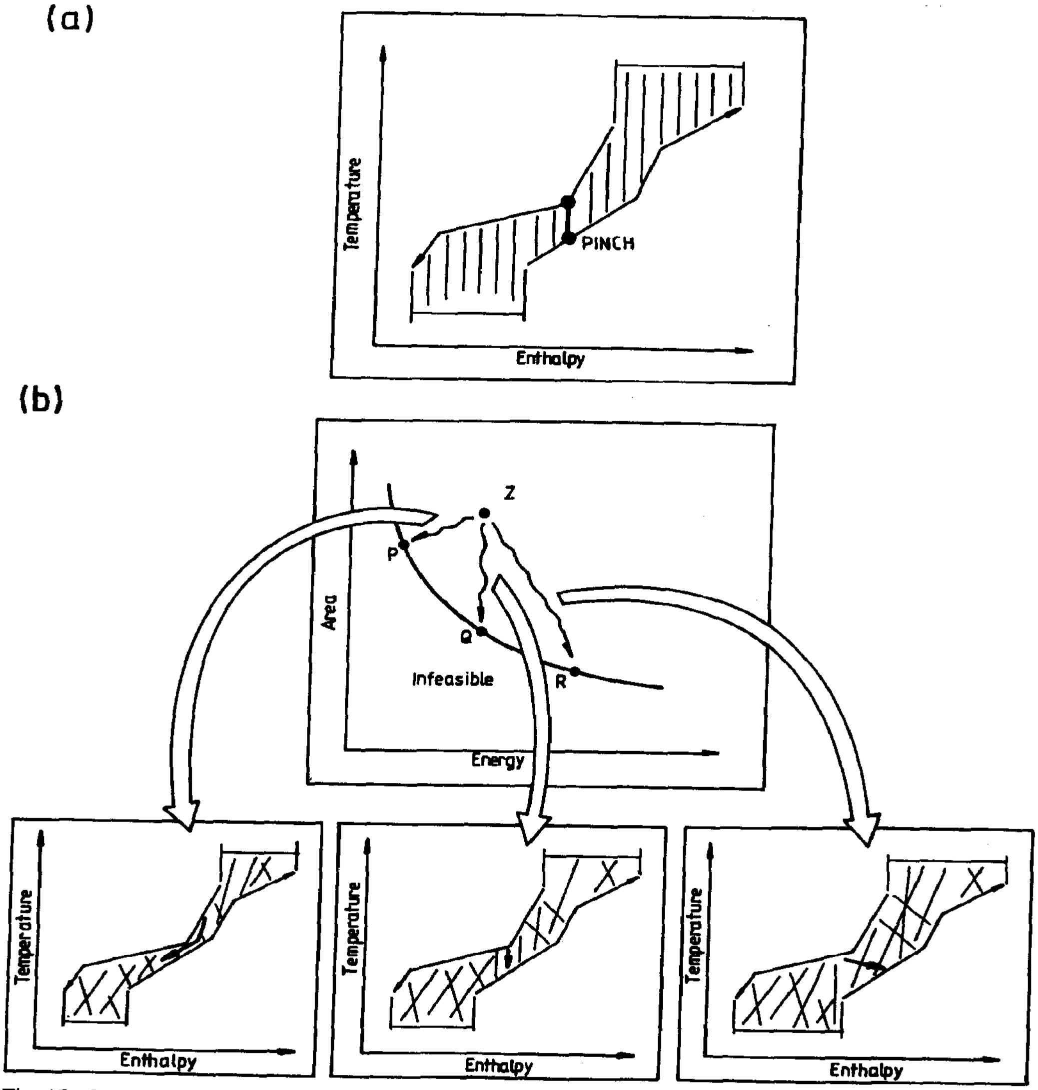


Fig. 17. Criss-crossing and cross-pinching: (a) no criss-crossing means no cross-pinch heat transfer; and (b) network Z, which shows criss-crossing, compared with the composites for points P, Q and R.

2. Now consider a design which has criss-crossing, point Z in Fig. 17b. Is it transferring heat across the pinch? Compared with the composite curves for point P, the network at Z has cross-pinch heat flow. To approach P, the design requires exchangers to be adjusted to avoid cross-pinch heat transfer.

   Compared with the composite curves for point Q, the network Z has the same energy and no overall cross-pinch heat flow. The design can be improved to point Q by correcting matches near or away from the pinch to make them vertical. Finally, compared with point R, network Z performs lower in energy. The design has exchangers with smaller temperatures differences than the $\Delta T_{\min}$ of the composite curves for point R. To bring Z to R needs these temperature differences to be increased by increasing the network energy consumption.

In summary, the non-optimality of network Z can result from cross-pinch heat transfer or criss-crossing. Under most cost scenarios network Z is non-optimal. Correcting the criss-crossing will also correct the cross-pinch heat flow and the design will assume a position on the target line. In doing so, it obtains the correct use of driving forces for its energy consumption. However, it may still be non-optimal in cost. To be close to optimal it must be located at a position on the line corresponding with the optimum $\Delta T_{\min}$.

Early work on heat exchanger networks recognized that cross-pinch heat flow should be avoided in order to achieve the energy target. A more general principle is now proposed. This recognizes that criss-crossing should be avoided if both the energy target *and* the area target of equation (8) are to be achieved.

5.3. Optimizing ΔT_{min} before design

The profiles of energy and area in Fig. 14 can be combined on a cost basis. A simple linear cost model is sufficient at this stage. (Part 2 of this paper will discuss the use of non-linear cost models):

annual network energy cost

$$= (Q_{\text{Hmin}} \cdot C_{\text{H}}) + (Q_{\text{Cmin}} \cdot C_{\text{C}}), \quad (11)$$

$$\text{exchanger installed capital cost} = a + b \cdot A, \quad (12)$$

where A is the exchanger area.

The network capital cost is then predicted by assuming the overall area target $A_{\min}$ is achieved in the minimum number of units for maximum energy recovery $U_{\min \cdot \text{MER}}$:

$$\text{network capital cost} = a \cdot U_{\min \cdot \text{MER}} + b \cdot A_{\min}. \quad (13)$$

To combine the two network cost elements for total annual cost requires annualization of the network capital cost by introducing a plant lifetime and rate of return (Ahmad, 1985). The resulting total cost profile displays a minimum at some value of $\Delta T_{\min}$. Both the position of the optimum as well as its cost depend on the physical process stream data and the economic data used (Ahmad and Linnhoff, 1984; Linnhoff and Ahmad, 1986).

5.4. Example

The example data in Table 1 has its target optimization profile shown in Fig. 18. We see that optimal

Table 1

Stream data

Stream	Specific heat × mass flow (CP) (MW°C^{-1})	Enthalpy change (MW)	Supply temperature (°C)	Target temperature (°C)	Heat transfer coefficient (MW m^{-2} °C^{-1})
1 hot	0.10	−28.70	327	40	0.50E − 03
2 hot	0.16	−9.60	220	160	0.40E − 03
3 hot	0.06	−9.60	220	60	0.14E − 03
4 hot	0.40	−46.00	160	45	0.30E − 03
5 cold	0.10	20.00	100	300	0.35E − 03
6 cold	0.07	9.03	35	164	0.70E − 03
7 cold	0.35	18.55	85	138	0.50E − 03
8 cold	0.06	6.60	60	170	0.14E − 03
9 cold	0.20	32.00	140	300	0.60E − 03

Utilities data

Hot utility (hot oil)	
Supply temperature:	330 (°C)
Target temperature:	Fixed at minimum of 250 (°C)
Heat transfer coefficient:	0.50E − 03 (MW m^{-2} °C^{-1})
Cold utility (cooling water)	
Supply temperature:	15 (°C)
Target temperature:	Fixed at minimum of 30 (°C)
Heat transfer coefficient:	0.50E − 03 (MW m^{-2} °C^{-1})

Cost data

Exchanger capital cost (\$) = 10,000 + 350 × area (m^2)

Plant lifetime: 5 (yr)
Rate of interest: 0 (%)

Annual cost of unit duty of hot utility: 60,000 (\$ MW · yr^{-1})
Annual cost of unit duty of cold utility: 6000 (\$ MW · yr^{-1})

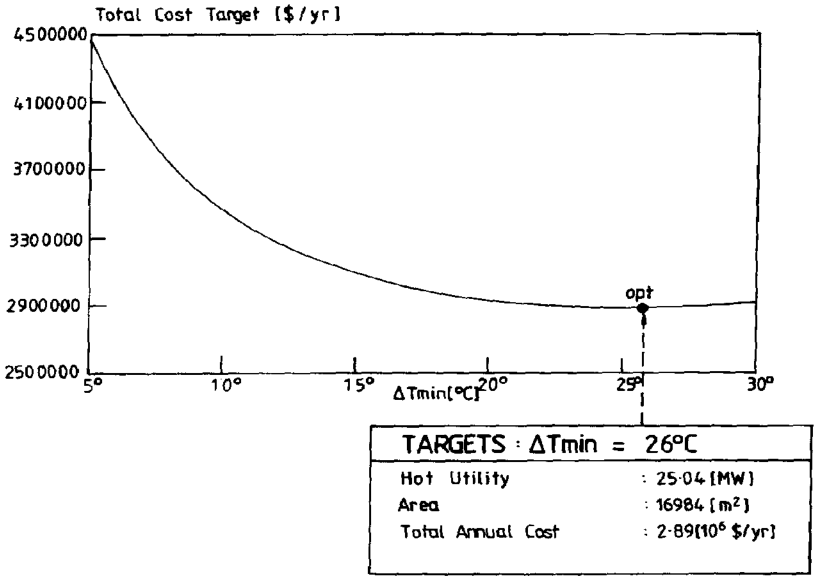


Fig. 18. Total cost target profile for example of Table 1.

design starts from $\Delta T_{min} = 26°C$. The Pinch Design Method and Driving Force Plot give the network in Fig. 19a. This design is on-target in energy, 4% above target in area (using two more matches than the minimum of 15), and within 2% of the optimum cost target. In an attempt to improve the network total cost evolution and continuous optimization of the exchanger duties can be performed by considering "loops", "paths" and any stream splits in the network (see Linnhoff and Hindmarsh, 1983; Hall *et al.*, 1989). Such an exercise leads to the network in Fig. 19b but with no appreciable improvement to total cost. This is to be expected if the targets are correctly optimized and closely achieved in the initial design. The final network in Fig. 19b is within 1% of the optimum cost target.

6. TOPOLOGY TRAPS

Networks designed at $\Delta T_{min} = 10°C$ and $\Delta T_{opt} = 26°C$ for the example in Table 1 are compared in Fig. 20. They have quite different structures. It would be extremely difficult to evolve the optimum design at 26°C from the network at 10°C.

Why do such different network structures result from different ΔT_{min} initializations? We observe that the pinch locations are different for the two designs in Fig. 20. Consequently, the stream populations either side of the pinch are different in each case. This means matching options at the pinch will also be different.

This phenomenon has been observed before but without much explanation (Ahmad and Linnhoff, 1986). It is particularly important to network optimization and requires some further understanding which will now be given. Figure 21 illustrates that several networks can be derived from the same stream data. Figure 21a shows that only the higher temperature pinch occurs at $\Delta T_{min} = 10°C$. In Fig. 21b, only the lower temperature pinch exists at $\Delta T_{min} = 26°C$. At about $\Delta T_{min} = 19°C$ the two pinches occur simultaneously (Fig. 21c). This is when the pinch "swap" takes place. As the pinches swap the stream population at the pinch also changes as seen from the grid diagrams in Fig. 21.

The structures which emerge from a given set of streams around the pinch can be classified as belonging to the same "topology region". Networks cannot normally be evolved from one topology region into another because the matching options can change dramatically. The topology regions are said to be separated by a "topology trap".

A network designed at a non-optimal value of ΔT_{min} will only reach the global optimum cost after evolution and continuous optimization of the exchanger duties if the initial structure is in the topology region containing ΔT_{opt}. Figure 22 shows this on our example problem. The optimization profile of the network at 10°C decreases in total cost until the energy consumption corresponds with about $\Delta T_{min} = 19°C$. Its cost cannot continue decreasing with the target profile unless the topology is now significantly changed. Networks designed above 19°C, however, are in the optimum cost topology region. The design at $\Delta T_{min} = 26°C$ performs close to target in the optimum region, but departs significantly in the non-optimum region.

The target profile can be regarded as close to the lower bound of all such network optima. The global optimum among these are structures in the topology region of the optimum ΔT_{min}. Given that topology traps can exist, target optimization will, at worst, save

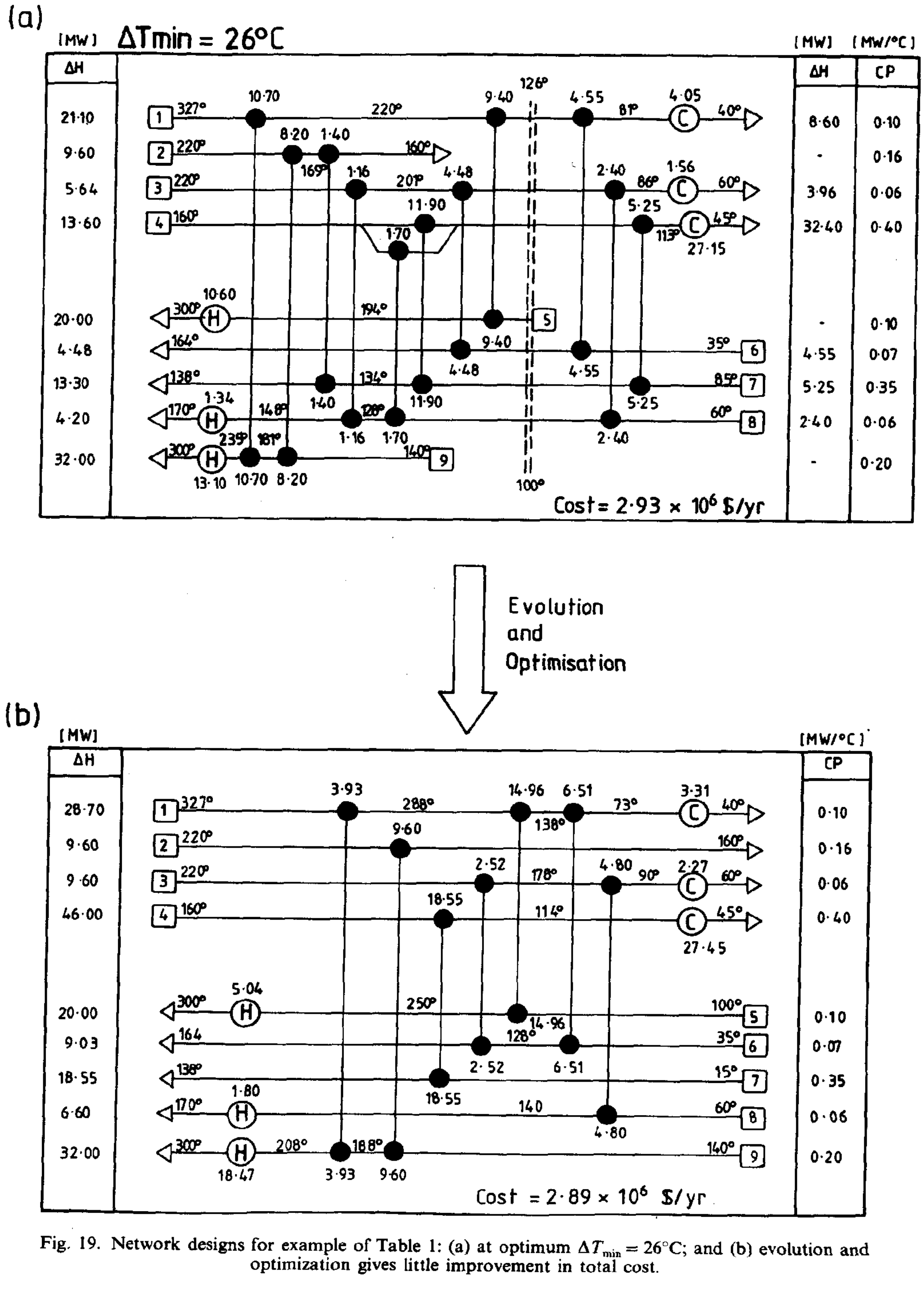


Fig. 19. Network designs for example of Table 1: (a) at optimum $\Delta T_{min} = 26°C$; and (b) evolution and optimization gives little improvement in total cost.

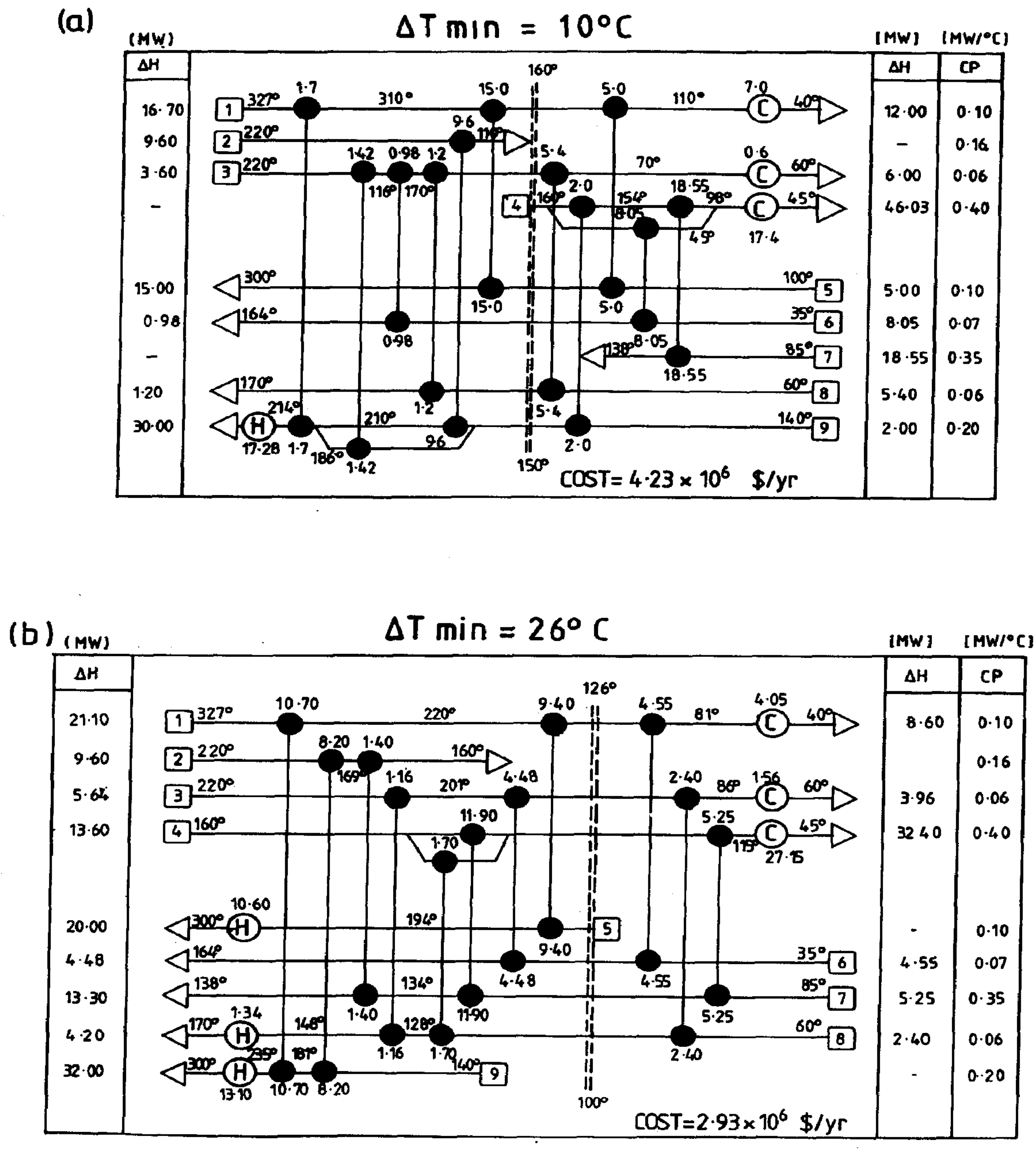


Fig. 20. Network designs for example of Table 1: (a) at $\Delta T_{min} = 10°C$ and (b) at $\Delta T_{min} = 26°C$. The network structures are quite different.

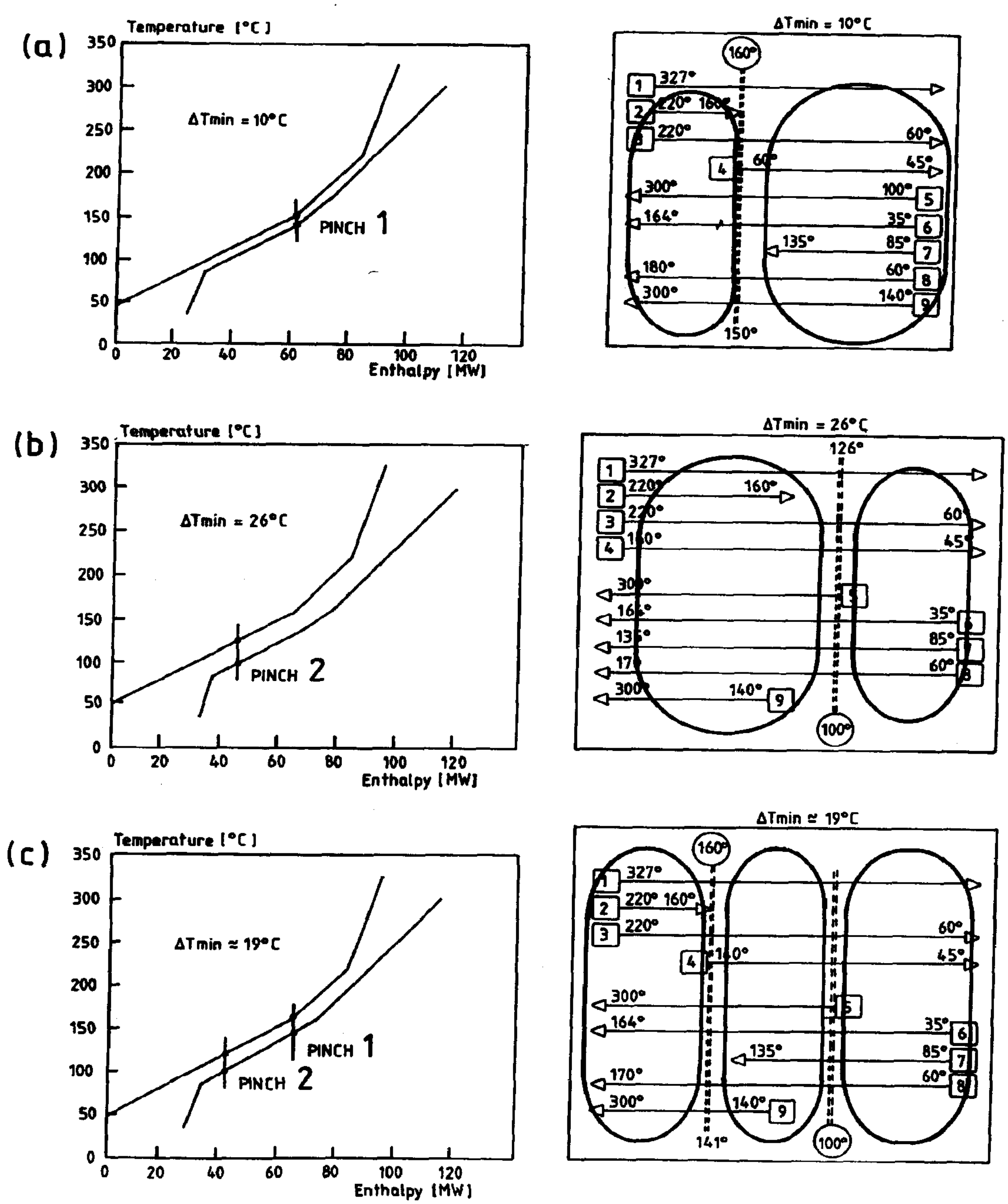


Fig. 21. Composite curves and grid diagram for example of Table 1: (a) $\Delta T_{min} = 10°C$; (b) $\Delta T_{min} = 26°C$; and (c) $\Delta T_{min} \simeq 19°C$. The pinch location and stream populations at the pinch depend upon the value of ΔT_{min}. The pinches swap at $\Delta T_{min} \simeq 19°C$.

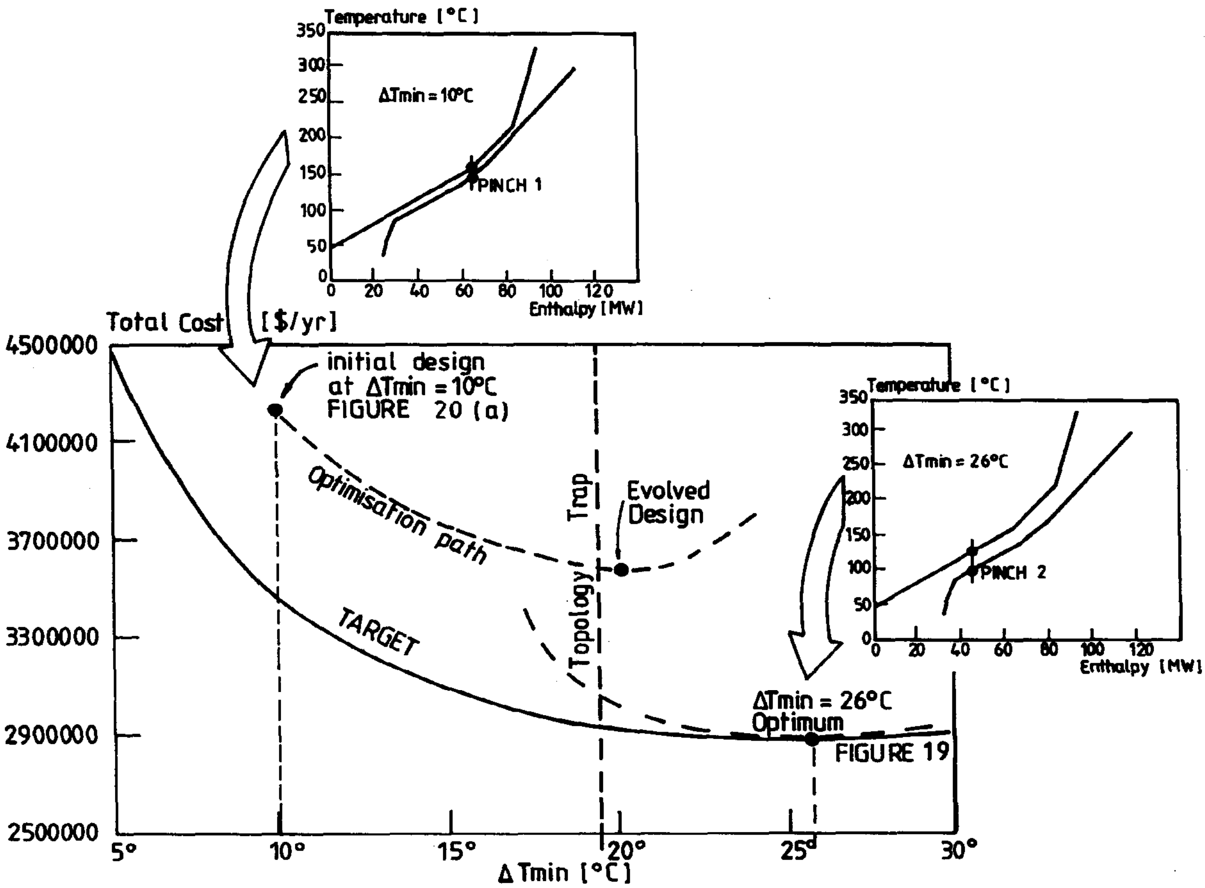


Fig. 22. Topology regions defined by the pinch location for network designs can be identified on the Total Cost Target Plot. Networks developed in a non-optimal topology region cannot be evolved to the global optimum cost by virtue of a "topology trap".

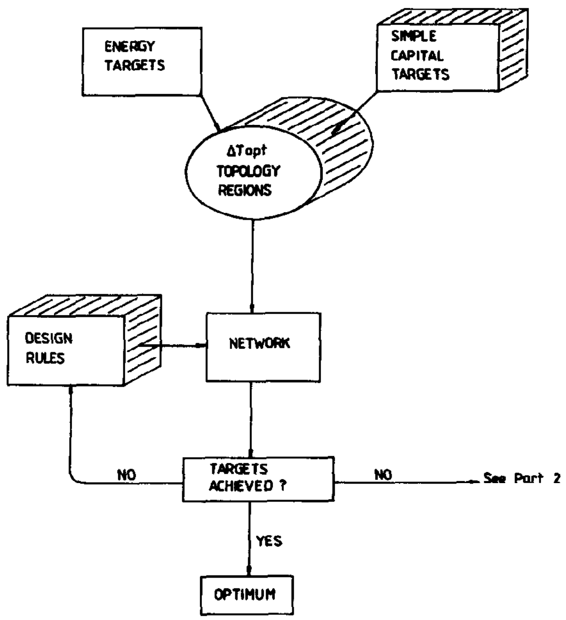


Fig. 23. Summary of procedure for designing optimum cost heat exchanger networks. Hatchured sections show the developments in this paper.

significant design time and, at best, yield substantially improved designs.

7. CONCLUSIONS

This paper offers some new understanding into the mechanisms governing the energy–capital tradeoff. Using a simple model of capital cost, a procedure emerges for the targeting and design of optimum cost networks (Fig. 23). More detailed capital cost models which can be incorporated into the procedure are discussed in Part 2 of this paper.

The procedure offers certain advantages:

1. Rapid pre-design optimization of networks. Different cost scenarios and process conditions can be scanned to locate the likely position of the global optimum network before evaluating any heat exchange equipment.
2. Systematic design techniques which require little or no evolution. Design to approach the global optimum cost can be achieved quickly.
3. The user can interact with the solution as it emerges such that the many intangibles of design such as safety, layout, etc. can be considered at an early stage.
4. The approach is practical even for large problems.

NOMENCLATURE

A = Heat exhanger area
A_i = Contribution to overall area target from enthalpy interval i of the composite curves [equation (7)]
A_{min} = Minimum overall area target for a heat exchanger network [equation (8)]
$A_{r \cdot M}$ = Area target for remaining stream data after accepting match M
$A_{total \cdot M}$ = Minimum overall area for heat exchanger network after accepting match M
$C_H(C_C)$ = Annual operating cost of unit duty of hot (cold) utility [equation (10)]
CP = Heat-capacity flowrate
ΔH_i = Total enthalpy change of enthalpy interval i on the composite curves
Q = Heat exchanger duty
$Q_{H\,min}(Q_{C\,min})$ = Minimum hot (cold) utility target
$T_{hot}(T_{cold})$ = Temperature of hot (cold) composite curve
ΔT = Temperature difference
$\Delta T_{LM \cdot i}$ = Logarithmic mean temperature difference (LMTD) for enthalpy interval i of the composite curves
ΔT_{min} = Minimum temperature difference on composite curves
U = Overall heat transfer coefficient for a heat exchanger
$U_{min \cdot MER}$ = Minimum number of units (matches) in a heat exchanger network with maximum energy recovery
a, b = Installed capital cost law coefficients [equation (11)]
a_M = Heat exchange area of match M
h_j = Heat transfer coefficient of stream j
$n_H(n_C)$ = Number of hot (cold) streams in an enthalpy interval
$(q_j)_i$ = Enthalpy change of stream j in enthalpy interval i of the composite curves

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