PINCH TECHNOLOGY : SUPERTARGETING For Optimum Synthesis of Energy Recovery Networks

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Abstract

Synthesis of optimum energy recovery networks in the context of overall process has been successful through the emergence of Pinch Technology. The procedures apply to energy systems involving heat exchanger networks, heat pumps, combined heat and power schemes (cogeneration) and utility systems. Basic Thermodynamics principles are applied to overall process to produce minimum energy targets before network design. Next, a design that satisfies the minimum energy requirements is synthesized by means of a few experienced-based design heuristics and fundamentals of Thermodynamics. The result is an approach that has gained success in over 500 industrial applications worldwide.

In the beginning of the development of Pinch Technology, minimum energy is of prime importance while concerns for network capital are largely brought in as an afterthought. An overall approach has recently emerged to bring together energy and capital cost targets before design. Near global optimality of the final design is virtually guaranteed, even for complex and highly constrained industrial problems. A key concept is that of supertargeting. This paper describes a case study application involving supertargeting and compares the approach to that of the current pinch design method which is based only on energy targets.

1 Introduction

The energy crisis in the early 1970's brought about much concern for better and more efficient process design. In the search for ways to improve energy and capital usage, Pinch Technology has emerged in the last ten years to prove that good integration pays off through simplicity of plant design and good use of energy and capital. The basic philosophy has been the need to set *targets before design*. The idea is to predict what should be achieved (targeting) and then set off to achieve it (design).

The pioneering work on Pinch Technology begins with the identification of energy targets for a process (Linhoff and Flower, 1978), and the recognition of the existence of heat recovery "pinch". The pinch is a temperature level in the process which limits the process energy recovery (Linhoff, Mason and Wardle, 1979). Next a design which satisfies the energy target is synthesized and the network structure is finally evolved to optimize energy against capital towards minimum total cost. Application to industrial projects resulted in significant savings, eventhough energy was the primary considerations (Linhoff and Turner, 1981; Linhoff and Vredeveld, 1984). The cost benefits over conventional techniques have been dramatic.

The procedures are based on thermodynamics principles and a few design heuristics used by engineers to manually synthesize the network. These procedures are applicable to

overall process and energy systems design comprised of one or more of the following components: heat exchanger networks (Linhoff and Hindmarsh, 1983), utility systems, combined heat and power cycles, and heat pumping systems (Linhoff and Townsend, 1982,1983). These components should be designed together, since interactions among them significantly determine the overall energy efficiency and capital costs (Linhoff and Ahmad, 1989)

More recently, the techniques have been extended to allow capital cost targets to be predicted ahead of design (Townsend and Linhoff, 1984; Ahmad, 1985). Energy and capital targets can thus be combined to generate a heat recovery network having a minimum total cost. The predicted targets are generated merely from the streams heat and material balance data of a process or a utility plant. Thereafter, the state of the art pinch procedure is applied to design a network that closely matches the minimum energy and capital targets. Near global minimum total cost is then achievable through the final structural evolution on the network.

A key concept is that of supertargeting. It allows energy and capital performance target to be compared and varied ahead of design to seek the optimum cost tradecff.

2 Energy Targets and the "Pinch"

From the heat and material balance data of any process, the stream data can be defined (Figure 1, Table 1 and Figure 2) (Mutalib and Manan, 1990) and the composite curves constructed (Figure 3 and 4) (Linhoff and Townsend, 1982).

The widths of the gaps at both ends of the composite curves define the minimum hot and the cold utility requirements of the process, or the energy targets. The targets are set ahead of design. It depend upon the smallest temperature difference occuring between the two curves known as the the minimum approach temperature, ΔTmin. The horizontal overlap of the curves determines the maximum possible heat recovery. As ΔTmin increases, the utility requirements will also increase. In the limit, no heat can be recovered from the process as the gaps between the curves widen, and horizontal overlap diminishes (Figure 5)

The point at which ΔTmin occurs is known as the heat recovery "pinch". The profound significance of the pinch is that it divides the system into two thermodynamically separate subsystems, each of which is in enthalpy balance with its relevant utility. Three design rules follow, which between them, guarantee minimum energy designs ;

no cold utility above the pinch
no hot utility below the pinch
no process heat recovery across the pinch

These results are rigorous. Grass-root designs can avoid cross-pinch heat transfer by placing heat exchanger matches above and below the pinch separately (Linhoff and Townsend, 1982). Retrofit designs should eliminate cross-pinch heat transfer by replacing existing equipment and avoiding the ΔTmin violation (Tjoe and Linhoff , 1986).

There exist a trade-off between the capital and operating costs as the ΔTmin is varied and the curves are shifted apart. An increase in ΔTmin will give a higher energy target and a higher energy cost. Plots of energy targets and energy costs against ΔTmin are shown in figure 6 and 7. As ΔTmin is increased, the energy cost increase is balanced by the capital cost reduction due to the reduction in the process to process heat transfer area required as the driving force for heat transfer increases. Associated with the energy-capital trade-off is an optimum ΔTmin value that yields a minimum total cost. Through Supertargeting, an approach has emerged to predict the minimum surface area requirement for any given

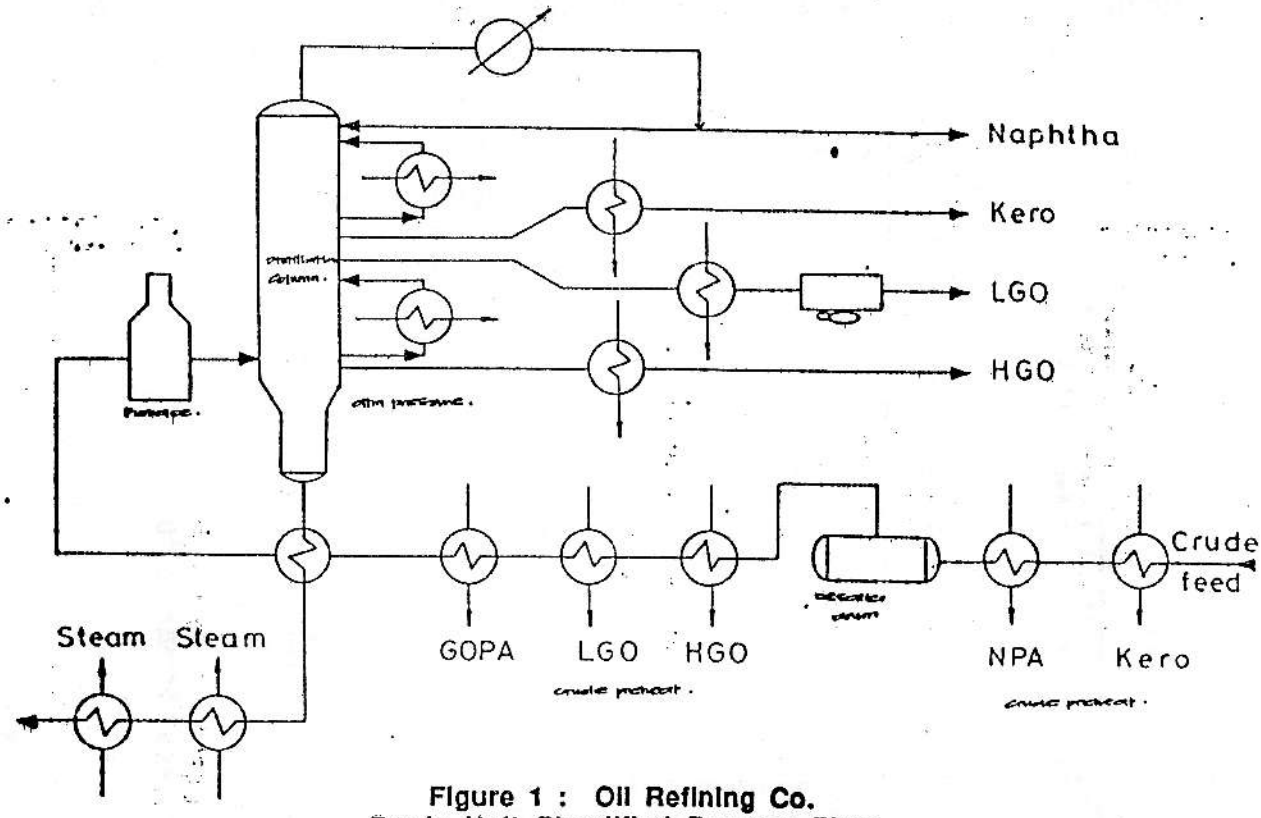

Figure 1 : Oil Refining Co.
Crude Unit Simplified Process Flow
Existing

Stream	Specific heat * mass flow (CP) [MW/C]	Enthalpy Change [MW]	Supply Temp [C]	Target Temp [C]	HTC [MW/m2/C]
1 Hot	0.47000	-47.00000	140.0	40.0	.800E-03
2 Hot	0.82500	-33.00000	160.0	120.0	.800E-03
3 Hot	0.04242	-7.00000	210.0	45.0	.800E-03
4 Hot	0.10000	-20.00000	260.0	60.0	.800E-03
5 Hot	0.35714	-25.00000	280.0	210.0	.800E-03
6 Hot	0.05000	-9.00000	350.0	170.0	.800E-03
7 Hot	0.13636	-30.00000	360.0	160.0	.800E-03
8 Cold	0.82609	95.00000	270.0	385.0	.800E-03
9 Cold	0.50000	70.00000	130.0	270.0	.800E-03
10 Cold	0.36364	40.00000	20.0	130.0	.800E-03

Table 1 : Stream Data Extracted From the Crude Unit Process Flow

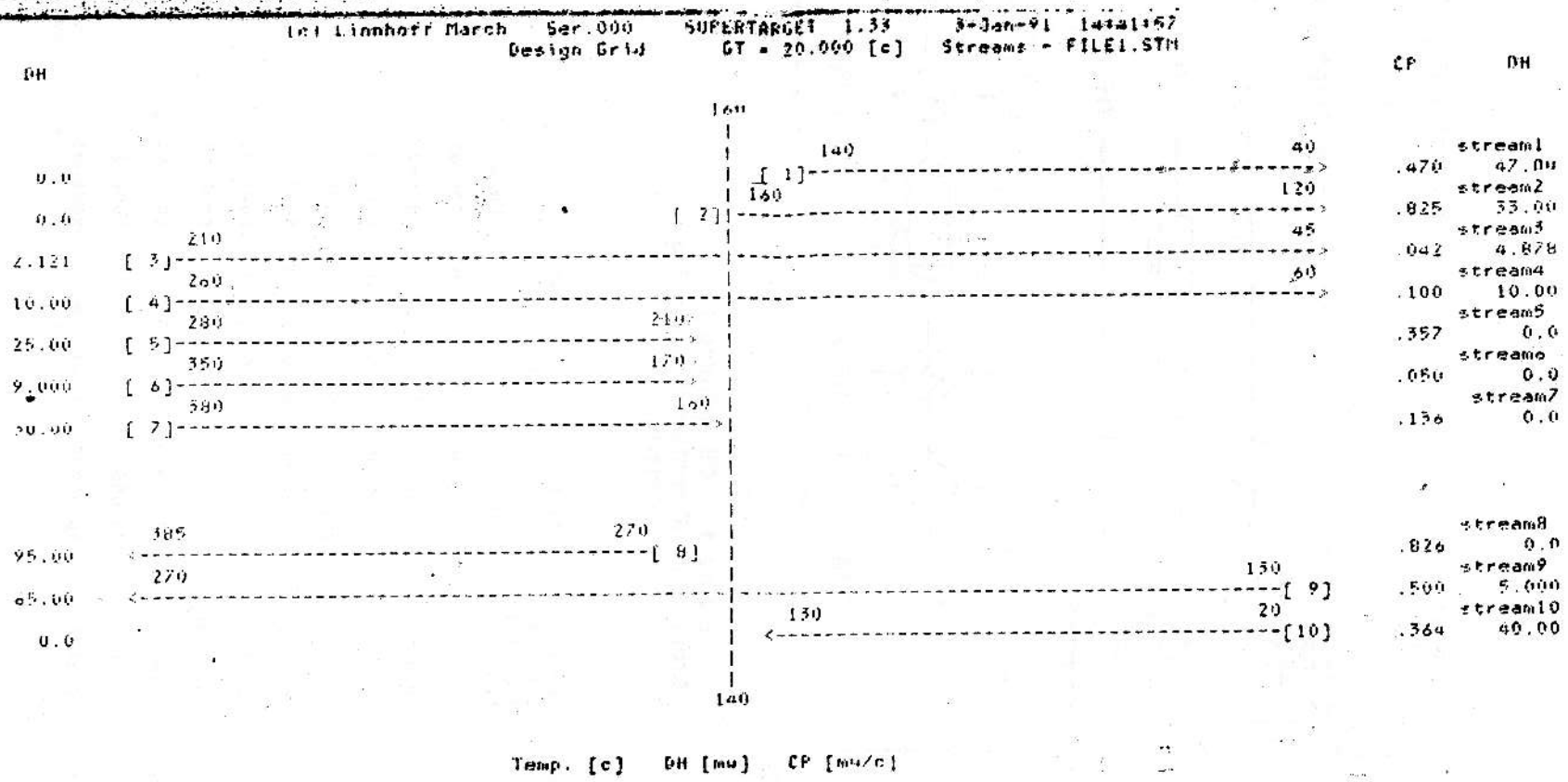

Figure 2: Process stream data

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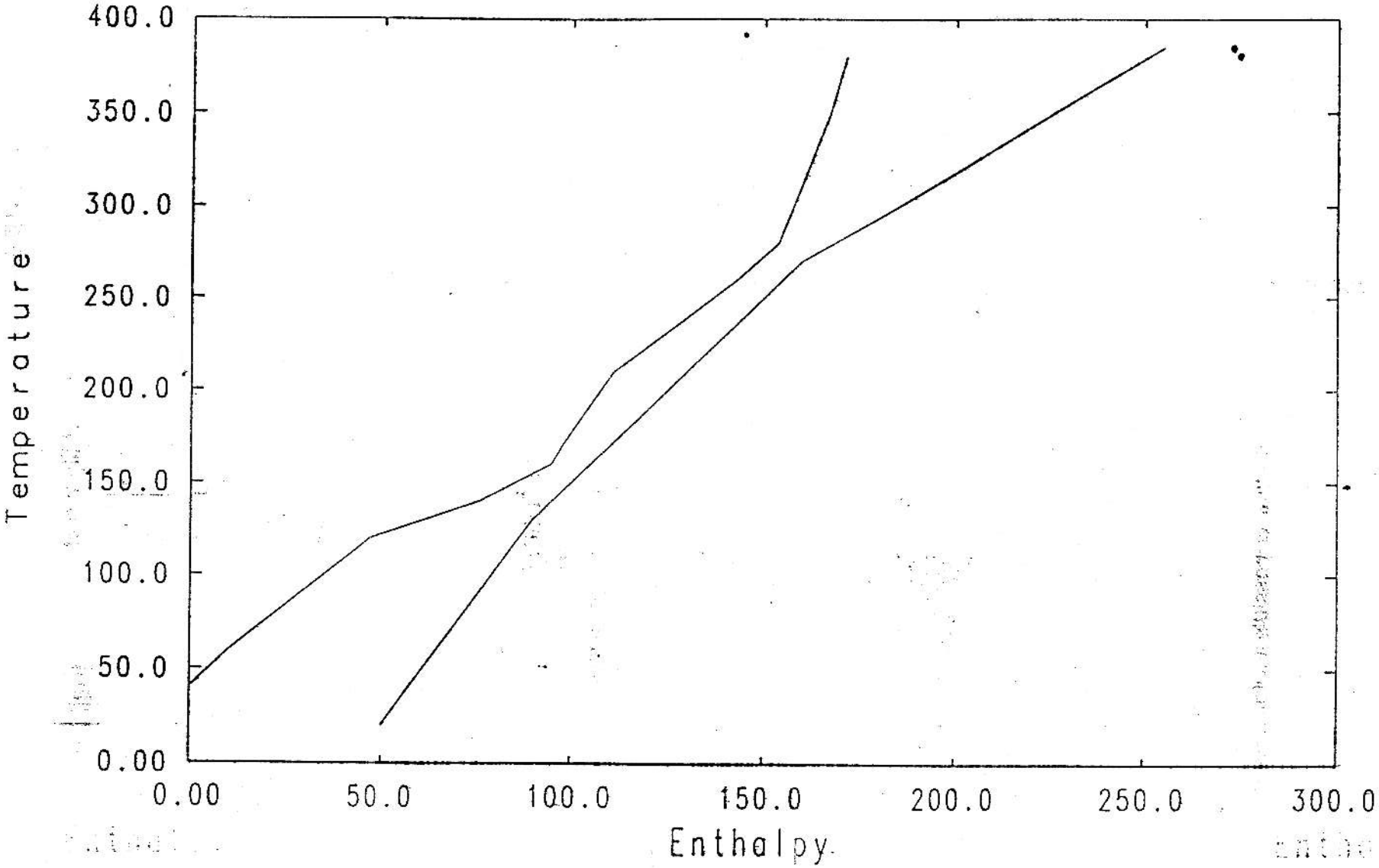
FIGURE 3: Composite Curves

DTmin = 20.0



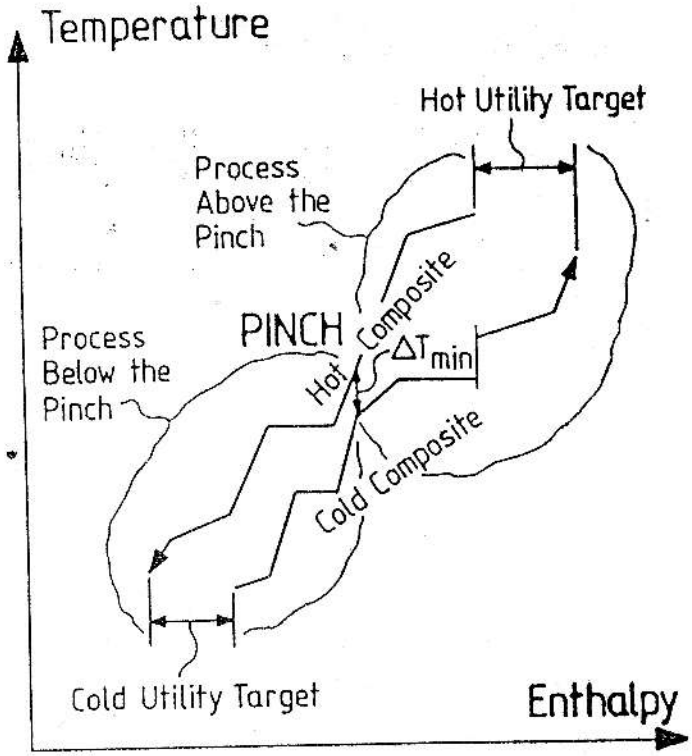


Figure 4 : Composite curves identify minimum energy requirements for a process and the pinch location

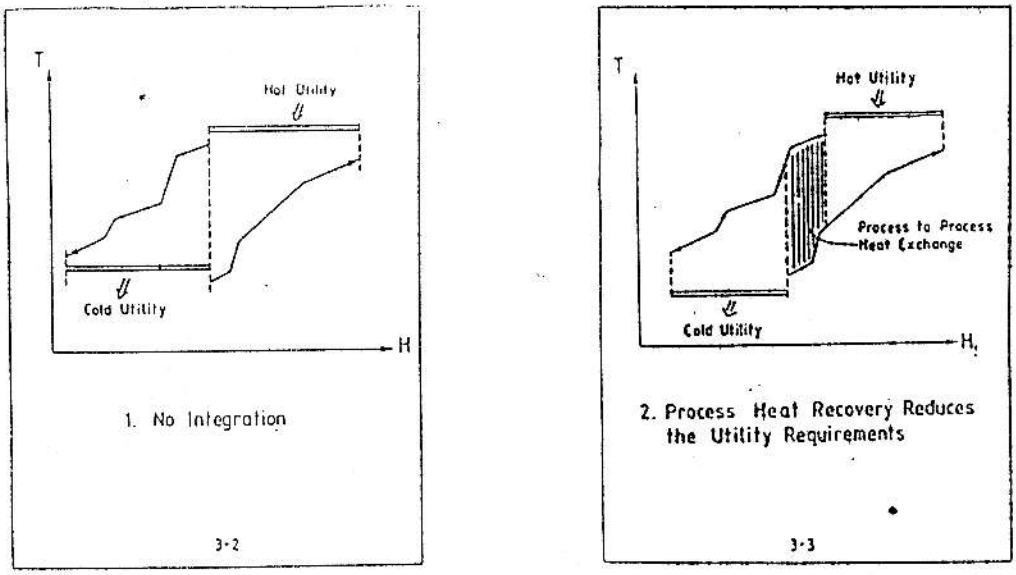


Figure 5. A limit is reached where no heat integration is possible as the curves are shifted apart

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Fig.6: DTmin - Energy Target Plot

DTmin = RANGE

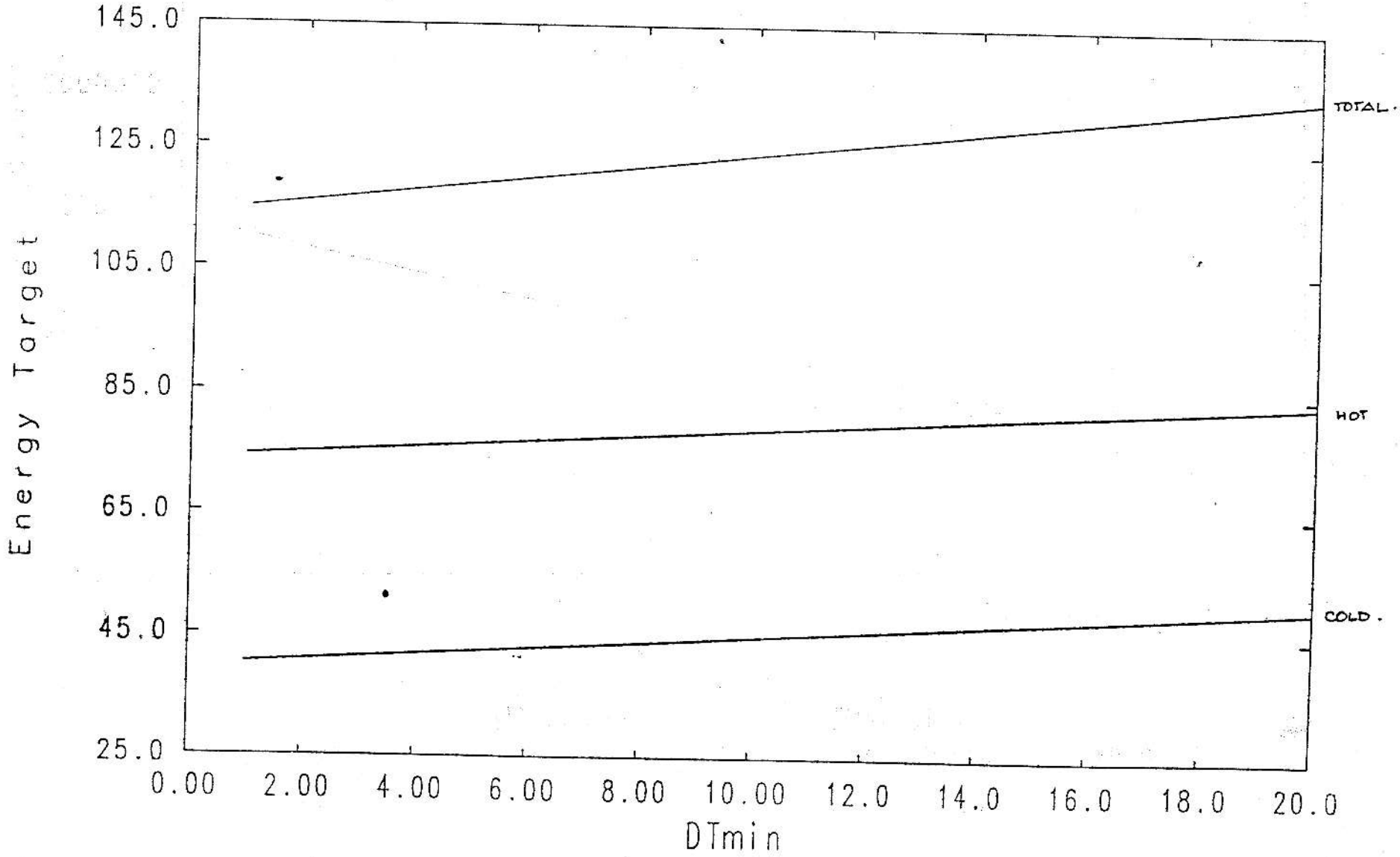

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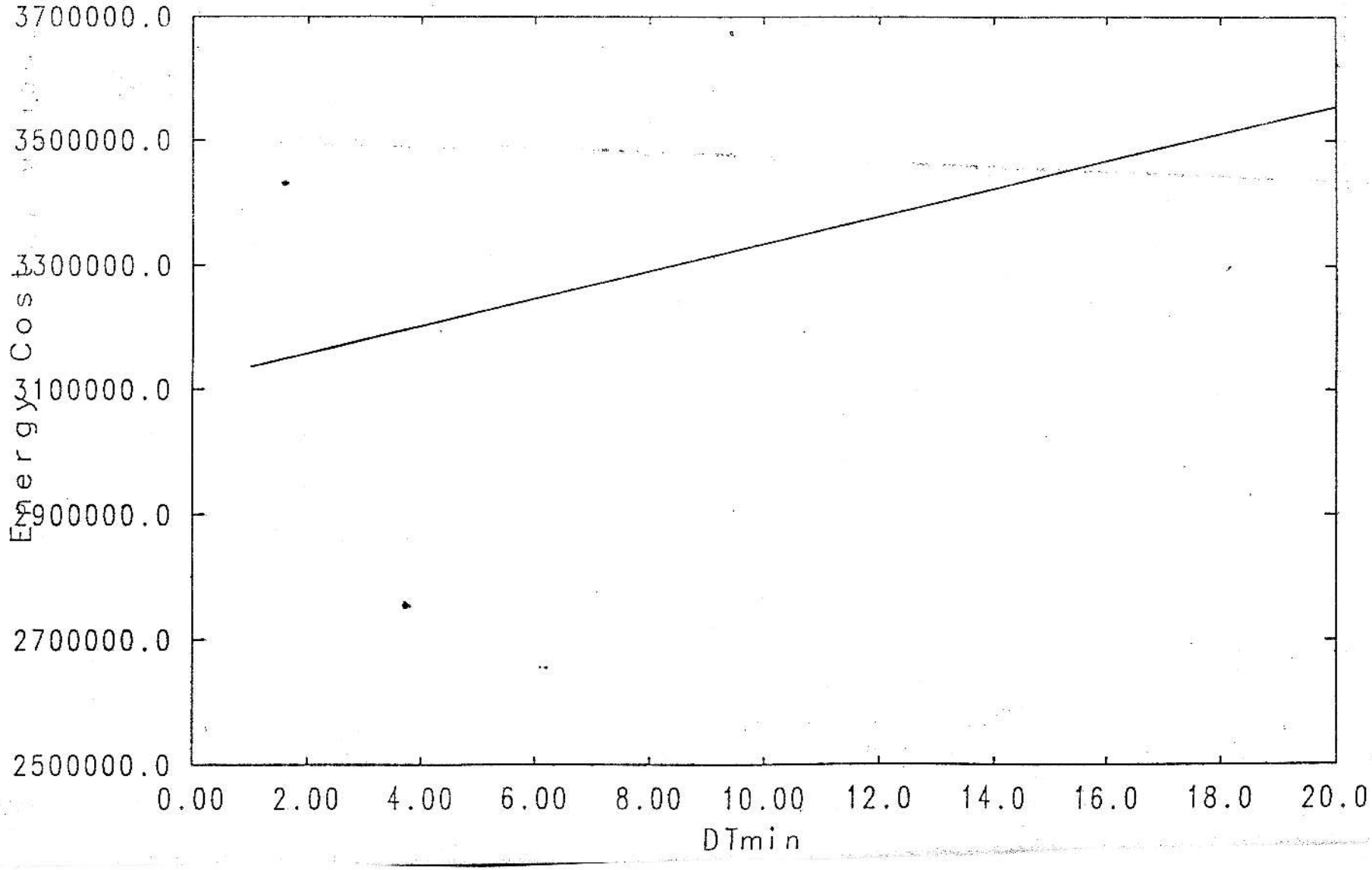
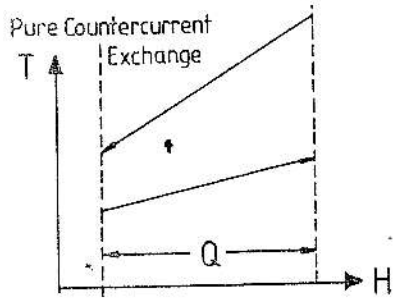
Fig.7: DTmin - Energy Cost Plot

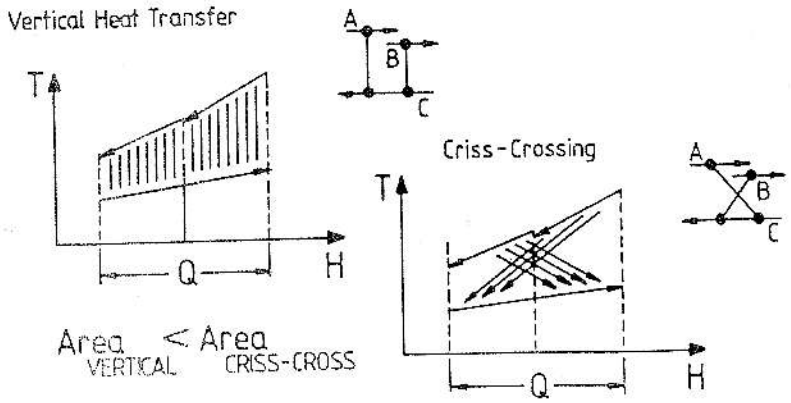
DTmin = RANGE



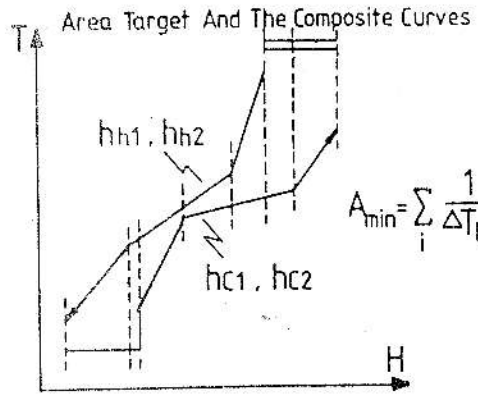


$$A = Q \;/\; U.\Delta T_{LH}$$

(a) In a single exchanger countercurrent heat transfer gives minimum area



(b) Countercurrent heat exchange on the composite curves appears as "vertical" heat transfer (as opposed to "criss-crossed") on the composite curves and gives minimum overall area



$$A_{min} = \sum_i \frac{1}{\Delta T_{LMi}} \left(\sum_j \frac{q_j}{h_j} \right)_i$$

(c) The vertical model leads to an expression for the minimum overall area target from the composite curves

Figure 8 : Surface area in heat exchanger networks

ΔTmin. In a wider context, the approach allows us to locate the optimum ΔTmin that is related to the minimum total network cost ahead of design (Ahmad and Shah, 1987).

3 Network Optimization Through SUPERTARGETING

a) Minimum Network Area

For any given ΔTmin, the minimum overall network surface area required for heat transfer can now be predicted ahead of design. This is a recent development in pinch technology that has successfully incorporated capital targets in the synthesis of energy recovery network (Townsend and Linhoff, 1984; Ahmad, 1985). It must be admitted that earlier works in the area has primarily been focused on the design for maximum energy recovery, while concerns for network capital were largely brought in as an afterthought.

The concept of minimum network area is an extension of the model for a single pure countercurrent heat exchanger. When the model is applied to the composite curves representing the entire network for a given value of ΔTmin, the countercurrent condition requires heat to be transferred vertically from the hot to the cold composite curve; rather than in some criss-crossed arrangement (see figure 8) (Linhoff and Ahmad, 1989)

It can be shown that the vertical heat transfer arrangement will result in approximately minimum overall network surface area. Any "non-vertical" match which gains the local advantage of a larger ΔT will be offset by the need for an opposite match with a lower ΔT. The net effect of such criss-crossing is usually an increase in the overall area requirement (see figure 9)

The expression for overall minimum network area is given in figure 8. This expression is derived from the analog expression for area $A = Q/(U\Delta T_{lm})$ for a single countercurrent heat exchanger. Q is the heat load for an enthalpy interval of the composite curve, ΔT_{lm} is the log mean temperature difference between the hot and the cold composite of a particular interval; h_{hi}'s and h_{ci}'s are taken as the heat transfer coefficients for the hot and cold streams of the interval respectively.

The expression is accurate to approximately 5% of the true minimum value (Linhoff and Ahmad, 1989) as the heat transfer coefficients differ significantly (up to one order of magnitude) especially for condensing steam. This accuracy is often adequate for targetting purposes and to obtain good design initiation. For better accuracy, more refined methods that takes into account the heat transfer coefficient, effects of different exchanger type, materials of construction, pressure ratings should be applied (Ahmad, 1985).

b) Network Surface Area Versus ΔTmin

The foregoing expression for the overall minimum network area varies inversely with the value of ΔTmin. Likewise, the same proportionality holds when the network capital cost is plotted against ΔTmin. Physically, as the driving force for heat transfer increases, the heat transfer area, thus the capital cost will be reduced, vice-versa. A useful relation between the capital cost target and the driving force, ΔTmin can thus be plotted from the cost data and stream data of a process (Figure 10) (Mutalib and Manan, 1990)

c) Number of Units Target

Applying the concept of pinch analysis , the minimum number of units is one less than the number of streams including utilities on each side of the pinch (Linhoff and Townsend,

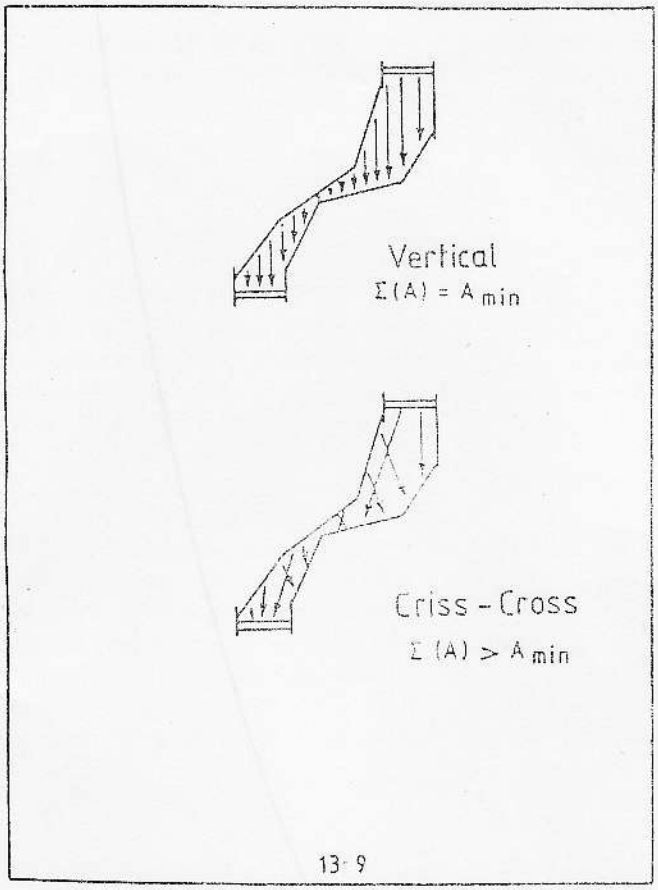


Figure 9: Vertical heat transfer gives minimum network area

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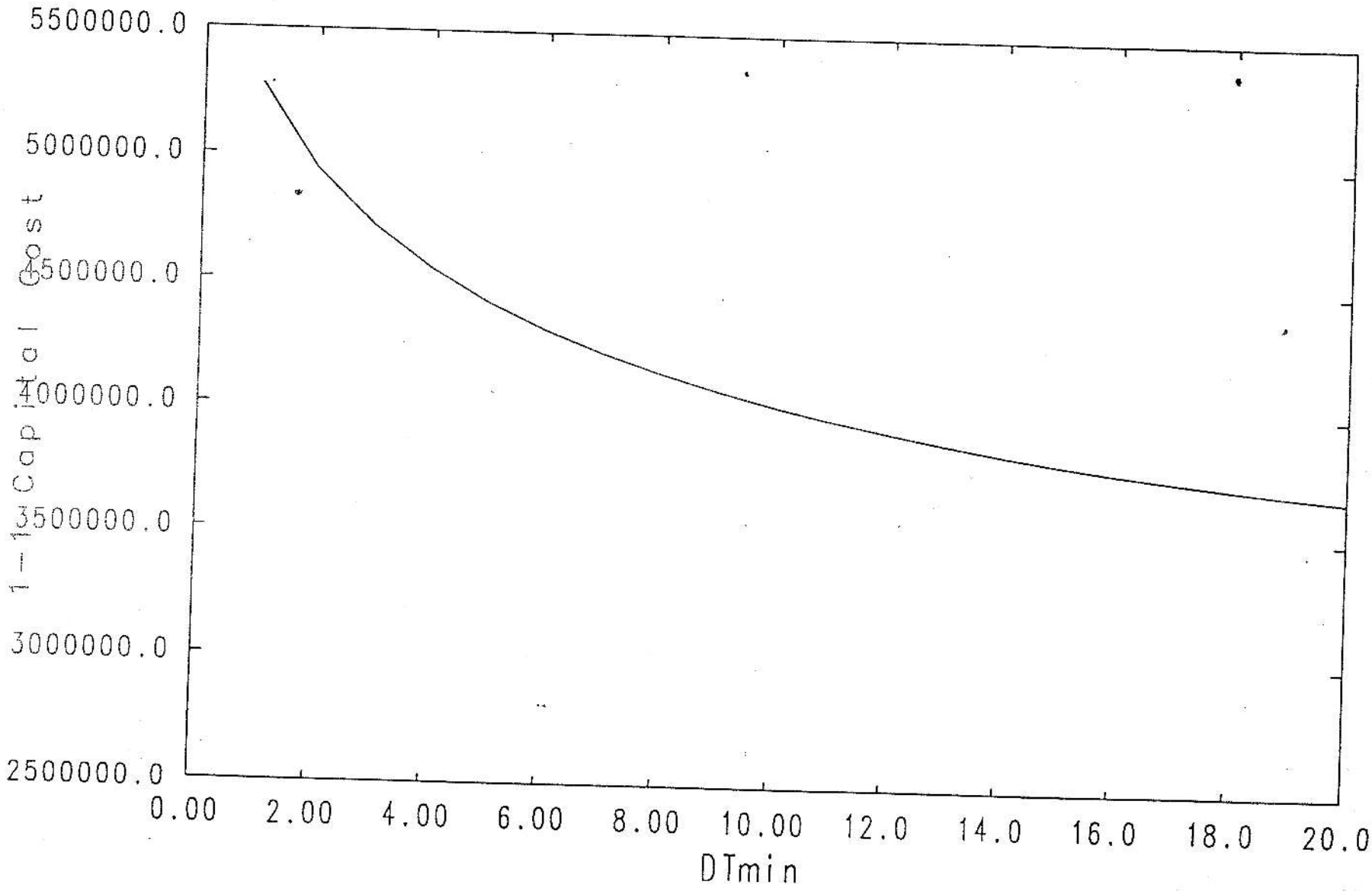
Fig. 10: DTmin - 1-1 Capital Cost Plot

DTmin = RANGE



1982). The total is the sum of units above and below the pinch. The minimum number of units is directly linked to the overall minimum network area which changes with ΔTmin.

d) Total Cost Target

The energy, capital and the number of units targets are unambiguously linked to the value of ΔTmin. By repeatedly obtaining these targets for a range of ΔTmin values, the combined annualized cost target profile as a function of ΔTmin can be generated as in figure 11 (Mutalib and Manan, 1990). In **Supertarget**, this profile is the most meaningful and important as it predicts the value of ΔTmin that gives the global minimum network total cost ahead of design, with no item of the equipment yet known.

Using the pinch approach, a heat recovery network can then be synthesized (Linhoff and Townsend, 1982) based on the ΔTmin value obtained from the total cost target profile. This procedure is known as supertargeting. It virtually guarantees near global optimality of the network for a given stream and cost data. Furthermore, design with supertargeting requires only a fraction of the effort compared to the designs which are based on lenghty and complex evolutions for capital optimizations.

4 Current Pinch Design Method : Application to An Aromatic Solvent Plant

The plant adopted for this case study is based on a simplified flowsheet for one of the largest aromatic complexes in Europe (Linhoff et al., 1982), figure 12. The feed-stock is naphta containing chiefly paraffins and cycloparaffins which are converted into products containing aromatic compounds. The reaction section shown in the flowsheet in figure 12 contains a complex and sensitive subset of streams which are not available or heat integration for reasons of start-up and safety. The process stream data subject to heat integration can be extracted from the plant heat and material balance. The individual streams are shown in the grid diagram (Linhoff et. al., 1982) of figure 13 together with the exisiting network. The heat exchanger network consumes 27.10 MW of hot utility. Using the economic data in Table 2 which can be regarded as typical European cost today, the existing network can be estimated to be installed as grass root design for an annual total cost (energy and capital) of 3.42 M$/year (Ahmad and Linhoff, 1989). The network was designed using conventional techniques as pinch technology was not known at that time.

Applying the pinch procedure, the stream data yields the composite curves and the energy target for a chosen value of ΔTmin (Figure 14). In the current pinch design method (summarized in figure 15), a value of ΔTmin = 10 C is chosen by engineers from their previous experience as reasonable for setting the tradeoff between energy and capital (Ahmad and Linhoff, 1989). For this assumption, an energy target of 17.28 MW is obtained for hot utility, some 36% below the existing usage (Ahmad and Linhoff, 1989). Using the **Pinch Design Method**, an initial heat exchanger network design that satifies the energy target can be synthesized (Linhoff and Hindmarsh, 1983). The network is then evolved to improve the energy-capital tradeoff by relaxing the minimum energy constraint. The evolution is somewhat complex but it is based on a well understood methodology (Linhoff et al., 1982) After the evolution the final network appears as in figure 16. The duties of the appropriate exchangers has been adjusted to correctly balance the overall network energy and capital cost requirements. The hot utility consumption is now 19.16MW and the total annual cost is about 3.18 M$ /yr.

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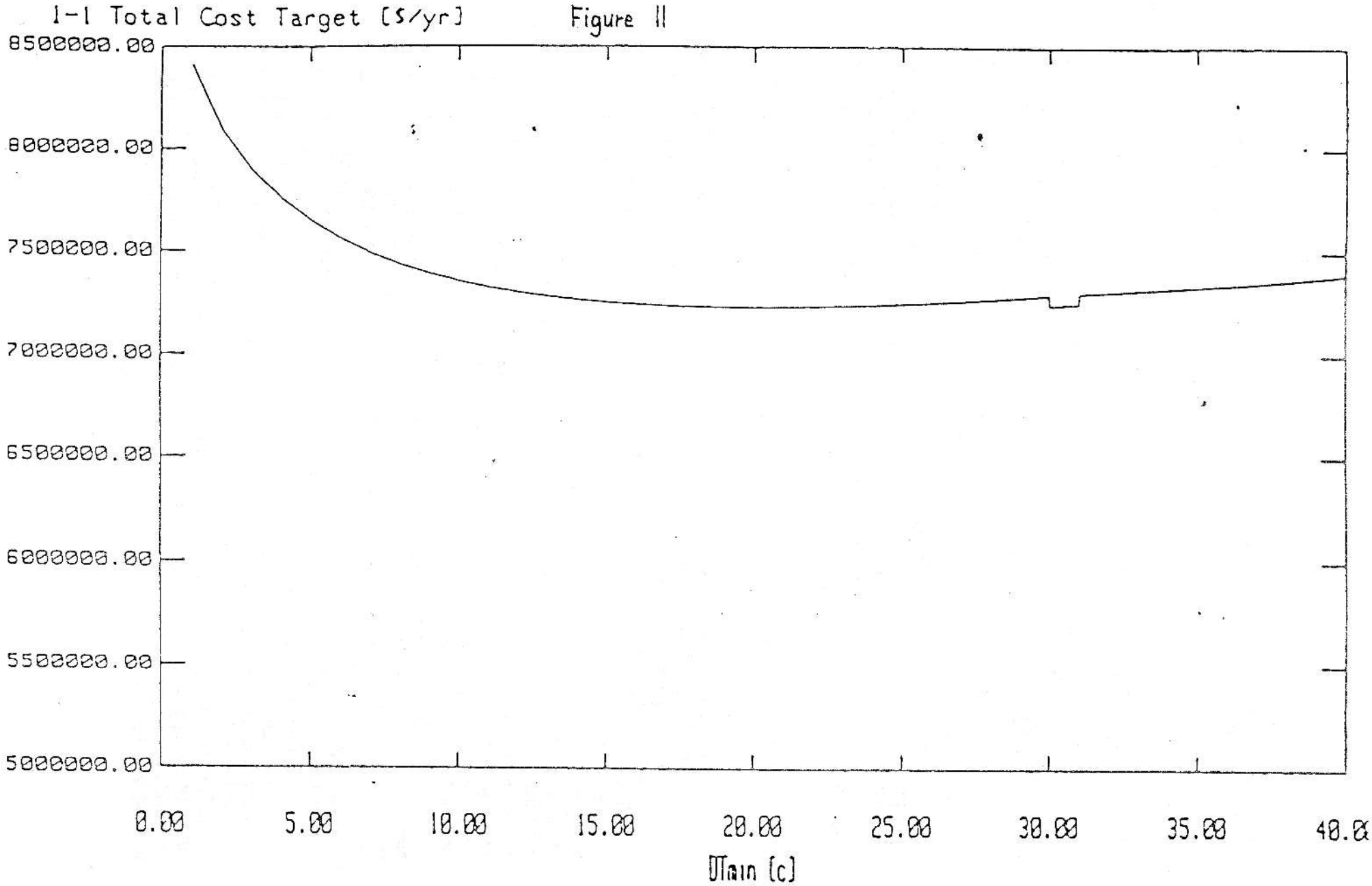
Streams - FILE1.STM Utilities - FILE1.UTY Costs - FILE1.CST



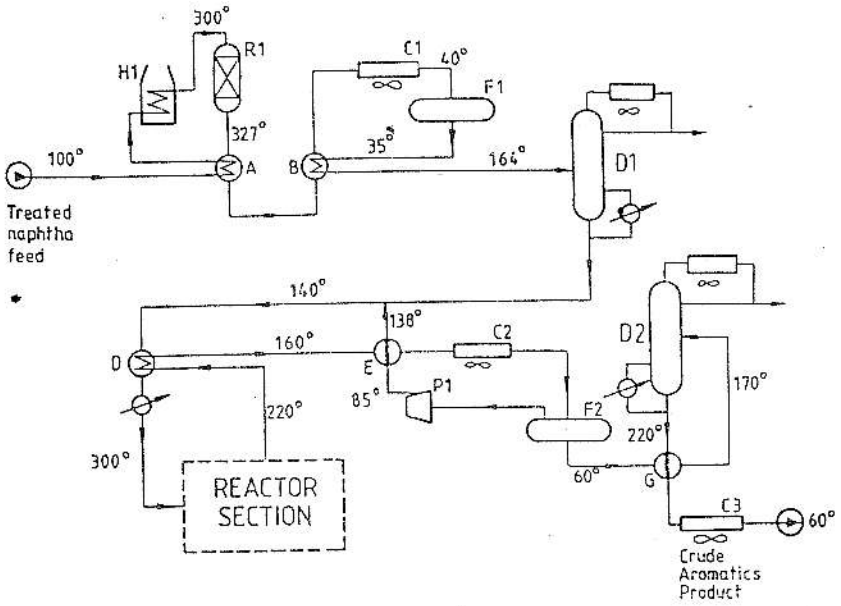


Figure 12 : Simplified flowsheet of aromatic solvents plant

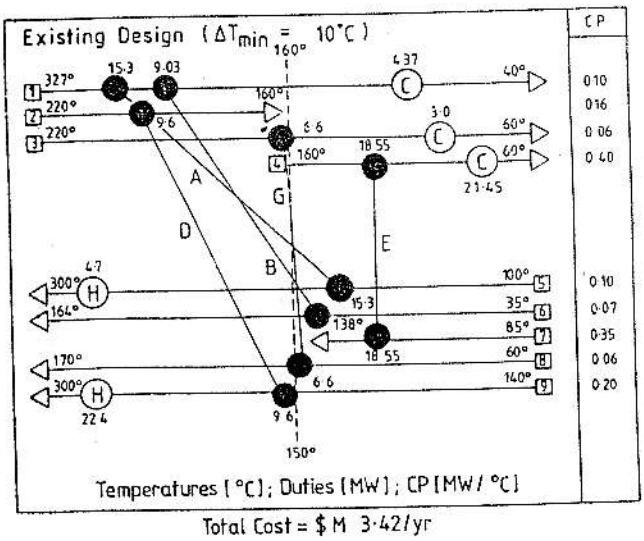


Figure 13 : The existing heat exchanger network for the aromatics plant shows cross -pinch heat flows, and therefore, more than minimum energy consumption for DTmin = 10 C

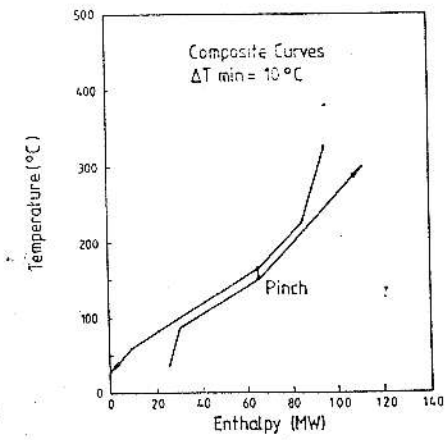


Figure 14 : Composite curves for DTmin = 10 C for the aromatics plant

Table 2. Cost data for European economics

Heat Exchangers:

Installed Unit Cost ($) = 700 $Area^{0.83}$ (m^2)

Heat transfer coefficient = 0.5E-3 ($MW/m^2 °C$)
all streams

Utility Data:

Hot Oil	: 75000 ($/MW.yr)
Cooling Water	: 10000 ($/MW.yr)
Temperature Hot Oil	: 330 °C
Temperature Cooling Water	: 15 °C

Plant Data:

Rate of Interest	: 5 %
Lifetime	: 5 years
Operation Time	: 8000 hours / yr

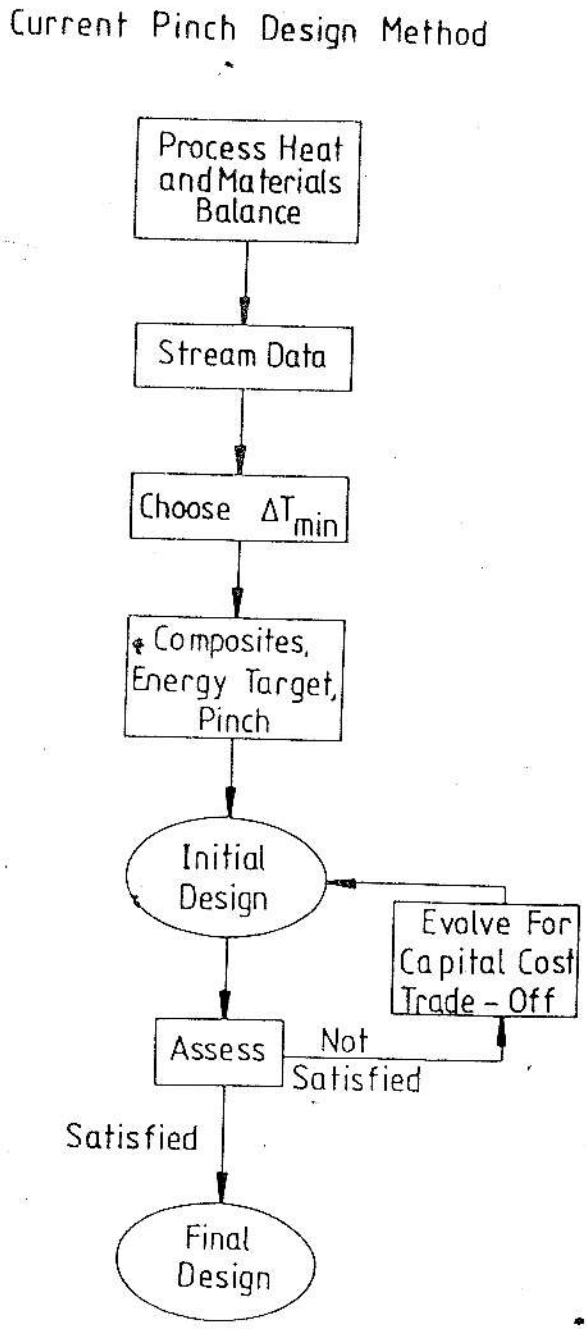
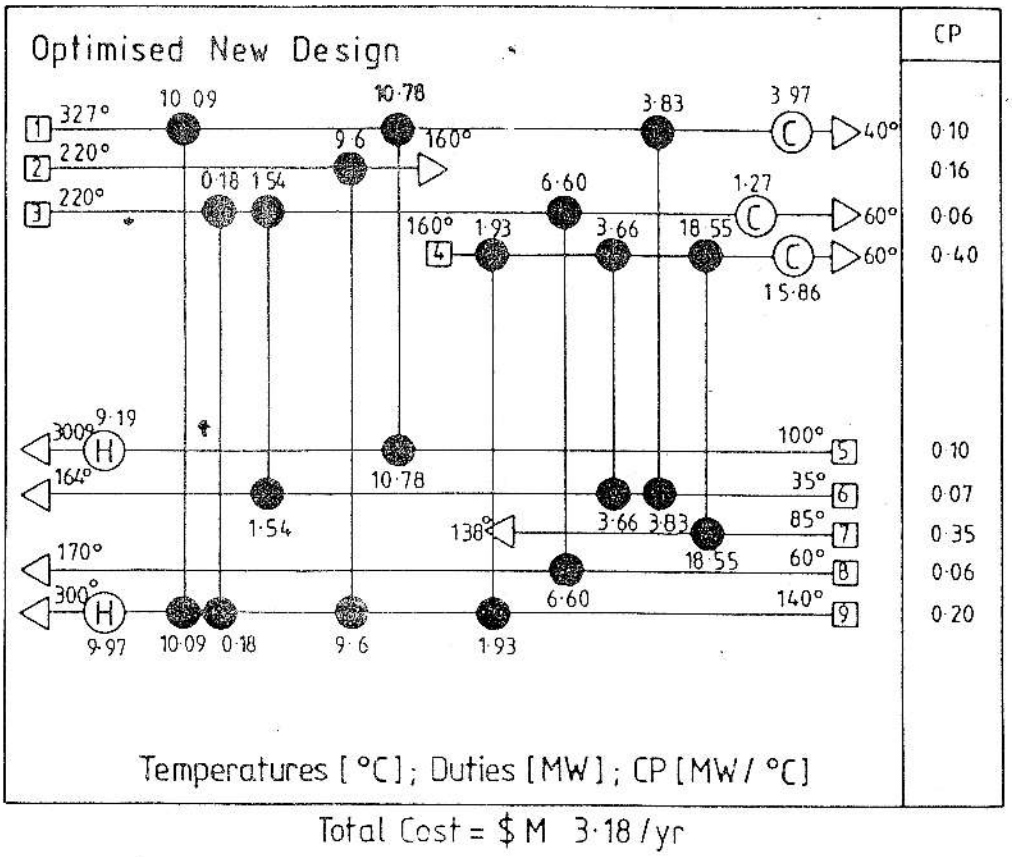


Figure 15 : Summary of basic pinch technology for heat exchanger networks : initial design is for minimum energy. Subsequent evolution and optimization correct the capital cost



Total Cost = $M 3·18/yr

Figure 16 : The minimum energy design can be evolved and optimized to correct for capital cost. The total cost is significantly reduced compared to that of the existing design.

5 Design Using Supertarget

The current pinch design method described in the foregoing illustrations shows how energy targets can be used to synthesize a heat exchanger network for the value of ΔTmin chosen. The design procedures emphasize on achieving the minimum energy target while the network capital optimizations are left to the final stage of the design. The final network evolution to seek the energy-capital tradeoff is lenghty and complex . It is largely based on the engineers experience and depends a great deal upon the ΔTmin initialization. Poor ΔTmin initialization can prove difficult to optimize (Linhoff and Ahmad, 1989). The procedure will result in a design that is near optimum only for the chosen value of ΔTmin. However, there is doubt wether different structures and different ΔTmin initializations would yield significantly improved results.

Consider now applying the supertargeting concept to examine the energy capital tradeoff for the aromatic plant described earlier. Given only the stream data from figure 13 and the cost data in table 2, the total cost target profile shown in figure 17 can be quickly generated. The curve suggests that the network should have been initialized at ΔTmin = 19 C instead of the experience value of 10 C as originally proposed. The design with ΔTmin = 19 C is predicted to have an energy target of 21.15 MW and a total annual cost of 3.00 M$/year. The design shows marginal improvement from the network cost of 3.18 M$/year achieved using energy targets alone. No design has yet been performed. After applying the pinch design method, the design at 19 C that satisfies the hot utility target of 21.15 MW is generated (figure 18). The total cost is found to be 3.15 M$/year, 5% off the minimum predicted by Supertarget. Optimization by conventional evolutionary methods produces no significant improvement in total cost (Ahmad and Linhoff, 1989)

Close match between target and actual design can be expected invariably (Ahmad, 1985). Closer examination of figure 18 reveals the design to be similar to that of figure 16. The results prove that Supertargeting can yield designs comparable or better than that based on complex evolutions with only a fraction of the effort.

Supertargeting not only incorporate capital targeting in its procedures but also eliminates the need for lenghty network evolutions to arrive at the global optimum cost. More importantly, the solution is guaranteed to be the global or somewhere near the global optimum value (Linhoff and Ahmad, 1989).

The approach as is powerful as it is simple. As has been explained earlier, the energy cost and the network capital cost targets are plotted against a wide range of ΔTmin values. The combined plot yields the total annual cost target as a function of ΔTmin. The value of ΔTmin for which the total cost is minimum can be easily obtained from the combined plot in figure 17. Consequently, the network is virtually optimized before ever seeing any design.

6 Significance

The current method of designing the heat recovery network is largely focused upon achieving the minimum energy target which is realizable from the experience-based ΔTmin. The task of seeking a good energy-capital tradeoff is left to the final lenghty phase of network evolutions and optimizations. As demonstrated in the foregoing case study on an aromatics process plant, the current pinch design method provides no guarantee that ΔTmin initializations other than 10 C will not result in a better network in terms of total cost. The design is optimum only for the chosen ΔTmin, but often there is doubt wether a different ΔTmin would yield significantly improved results.

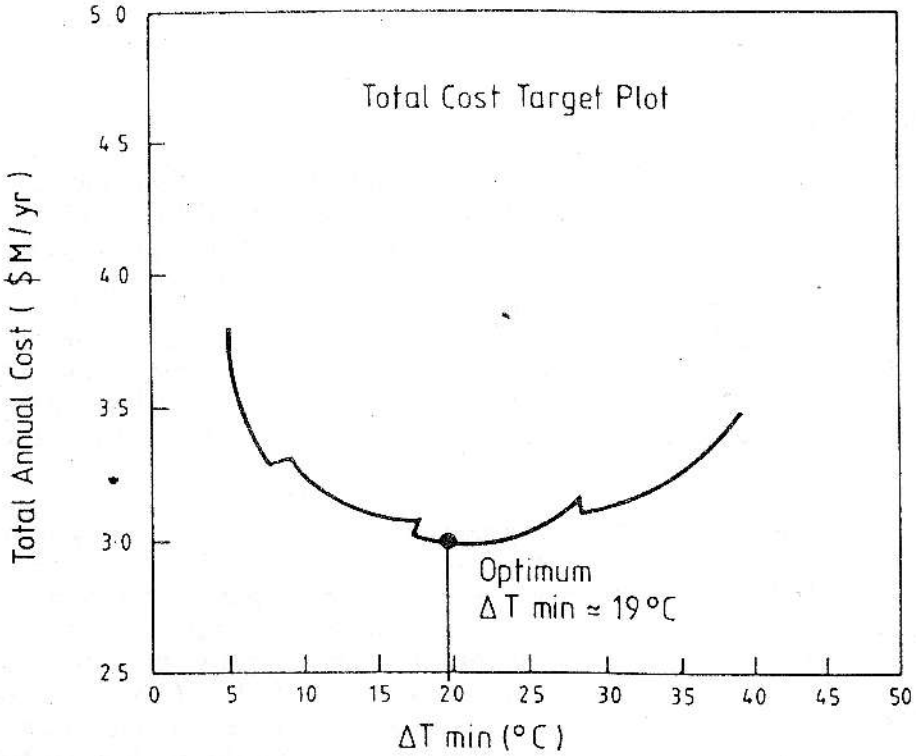


Figure 17 : The targets for energy and area can have cost data applied to predict the total cost target profile. For the aromatics plant this gives optimum ΔTmin = 19 C

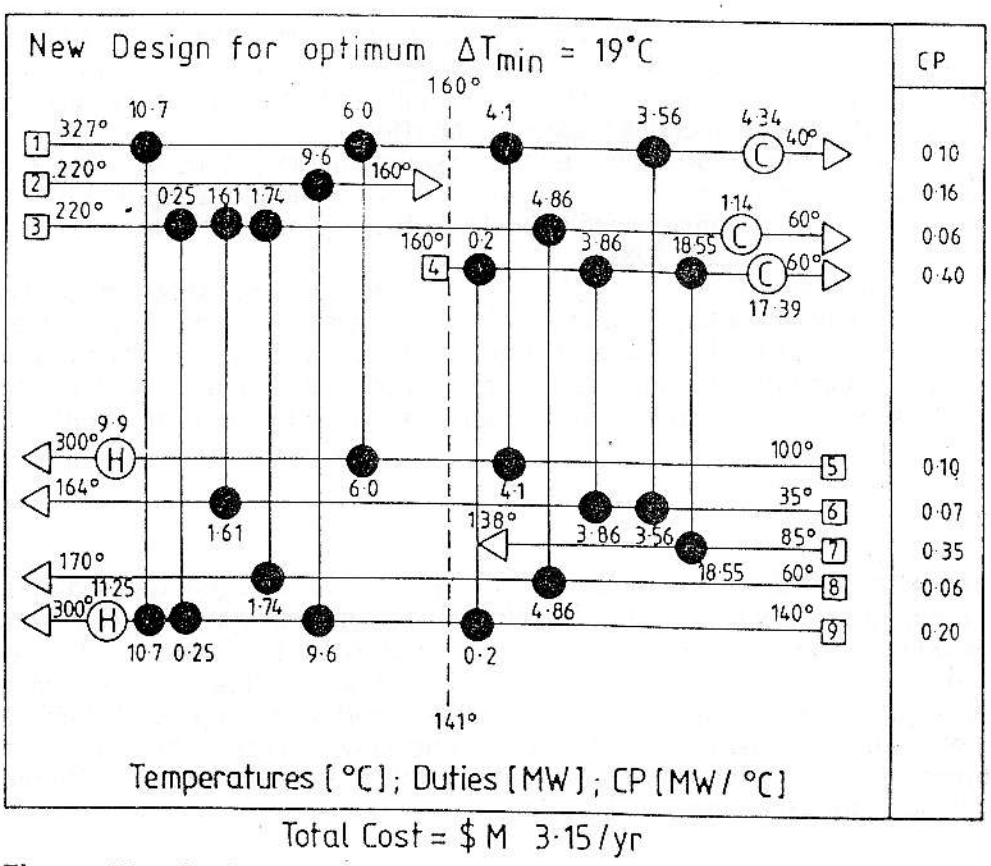


Figure 18 : An initial minimum energy design for the aromatics plant at optimum DTmin = 19 C. Its performance is close to the predicted total cost target and is significantly lower than that of the existing design. Compared to the evolved and optimized design form DTmin = 10 C (Fig. 6), the total cost is similar but is obtained with much less effort.

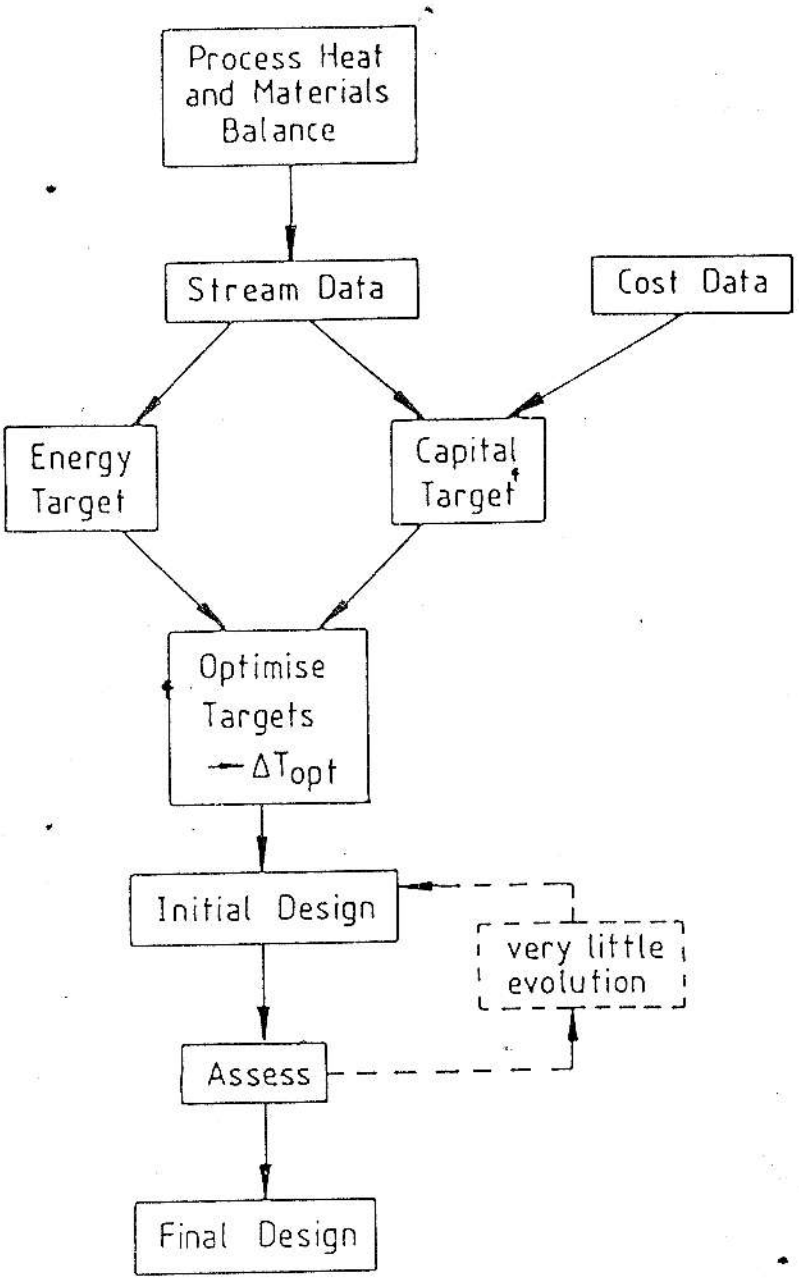


Fig. 19 Summary of the supertargeting procedure: energy and capital targets are optimized before design. Initial designs based on the optimum value of ΔT_{min} require virtually no evolution and are near the global optimum total cost.

Supertargeting is able to solve this uncertainty by introducing the concepts of capital and energy targets *before design*. Supertargeting allows a user to scan the entire spectrum of design structures and ΔTmin values to locate the near global optimum network with absolute certainty before designing any single piece of equipment. The result is quickly obtained since tedious network evolutions are eliminated. Supertargeting, implemented by a suitable software allows us this rapid and effective examination of the energy and capital tradeoffs for an entire process or even an entire site, however complex, using only streams heat and material balance data and economics data for a given process.

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