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A Note on Targeting in the Design of Cost Optimal Heat Exchanger Networks

J. Jezowski* and F. Friedler**

*Institute of Chemical Engineering and Heating Equipment,
Wrocław Technical University, Wrocław, ul. Norwida 4/6, Poland

**Research Institute for Technical Chemistry of the Hungarian
Academy of Sciences, Veszprem, Schonherz Z.u.2, H-8201 Hungary

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Current computerized approaches to heat exchanger network (HEN) synthesis usually require the minimum temperature approach as well as types, parameters and heat loads of utilities as input data. These parameters influence greatly the overall cost of the solution. The "good" values of the parameters can be evaluated in the pre-design stage - by the use of targeting procedures.

Ahmad and *Linnhoff*[1,2,3] and recently *Ahmad* and *Smith*[4] presented the application of the targeting methods for prediction of a "good" value of the minimum temperature approach ($\Delta T^{\min}$). Here we present the development of a simple methodology for predicting the good values of all decision variables in HEN synthesis, i.e. $\Delta T^{\min}$ and heat loads of utilities. The application of this approach is illustrated by examples, including industrial problems. A comprehensive review of the current methods of calculating targets is also given in the paper.

Key words:
Heat exchanger network, synthesis, cost, optimization, targets

Introduction - criteria for HEN

The overall cost of a heat exchanger network (HEN) E, i.e. the cost of energy E_u and capital cost of apparatus C_a, is the major criterion for a HEN:

$$E = E_u + C_a \tag{1}$$

Cost of energy for heating and cooling is calculated from eq. (2) (note that energy cost for pumping fluids is omitted here).

$$E_u = \sum_{m=1}^{N_{HU}} Q_{hu,m} \cdot p_{hu,m} + \sum_{n=1}^{N_{CU}} Q_{cu,n} \cdot p_{cu,n} \tag{2}$$

Equation (3) is applied to estimate purchase and installation costs of apparatus, i.e. heat exchangers, heaters and coolers (in the case of a furnace another equation is used).

$$C_a = \sum_{k=1}^{N_A} \left(a_k + b_k \cdot A_k^{\sigma_\kappa}\right) \tag{3}$$

It is convenient to modify eq. (3) so as to use the number of matches and the number of shells for each match:

$$C_a = \sum_{k=1}^{N_M} \left(a_k + b_k \;\; A_i^{\sigma_\kappa}\right) \cdot N_{S,k} \tag{4}$$

where: A_i – area of a shell in k-th match

To account for the piping and maintenance expenses, the capital cost of apparatus from eq. (4) is multiplied by factor F_p (see *Trivedi* et al.[5]). Equation (5) includes costs of extra piping caused by stream splits.

$$F_p = \left[\beta\left\{1 + \left[\frac{N_{nod}}{N_M^{\;\min}}\right]^{\gamma}\right\}\right]\left[\frac{1}{M} + \Phi\right] \tag{5}$$

where: $N_{nod} = 2 \cdot N_{spl}$

β, γ, M, Φ = cost. parameters

There is a possibility of predicting a value of E prior to the synthesis by using a substitute criterion $\overline{E}$. Substitute criteria for Ca and calculation methods have been suggested by *Townsend* and *Linnhoff*[6] (eq.6) as well as *Ahmad* and *Smith*[4] - eq.(7).

$$\overline{C}_{a_1} = N_M^{\;\min} \cdot \left[a + b \cdot \left\{\frac{A_{o1}^{\;\min}}{N_M^{\;\min}}\right\}\right] \tag{6}$$

$$\overline{C}_{a_2} = N_S^{\;\min} \;\; \left[a + b \cdot \left\{\frac{A_{o2}^{\;\min}}{N_S^{\;\min}}\right.\right] \tag{7}$$

The value of E_u can be approached by $\overline{E}_u$ from eq. (8).

$$\overline{E}_u = \sum_{m=1}^{N_{HU}} Q_{hu,m}^{\min} \cdot p_{hu,m} + \sum_{n=1}^{N_{CU}} Q_{cu,n}^{\min} \cdot p_{cu,n} \tag{8}$$

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*Author to whom correspondence should be addressed.
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Substituting N_M by N_M^{min} and N_S by N_S^{min} in eq. (5) for F_p it is possible to estimate the cost of piping. It is worthwhile noting that the values of energy cost and capital expenses computed from substitute functions (6), (7), (8) are supposed to be the optimal values of C_a and E_u for a HEN. The parameters in the equations, i.e. A_{o1}^{min}, A_{o2}^{min}, N_M^{min}, N_S^{min}, $Q_{hu,m}^{min}$, $Q_{cu,n}^{min}$ and N_{sp1}^{min}, are commonly called the targets. Such targets as well the values of the substitute criteria are applied to:

1) determining proper (optimal) values of minimum temperature approaches for HEN synthesis,
2) "control" HEN synthesis in the so called "remaining task analysis" approaches (e.g.[5]).

An important application of the targets is development of the rules for aiding synthesis.

This paper has the following aim:

to show the necessity of determining the proper values of the types and heat loads of utilities prior to the synthesis, i.e. in the targeting stage.

We will also show that a substitute function $\overline{C}_{a2}$ from eq. (7) gives results that are precise enough for practical applications.

Methods for calculating targets

The value of the targets in substitute functions (6), (7), (8) should be optimal for the overall cost E. The current methods of calculating the targets enable the user to determine such values of targets that (for a given temperature approach) are the minimal ones. For instance, it is possible to calculate N_M^{min} which is the minimum for the task considered but is not necesserily optimum for the cost of a HEN. In spite of this, the application of such minimal values gives quite reasonable predictions of the value of E.

In this section, we will shortly describe the approaches to determining values of the following targets: $Q_{hu,m}^{min}$ $(m=1,...,N_{HU})$, $Q_{cu,n}^{min}$ $(n=1,...,N_{CU})$, A_{o1}^{min}, A_{o2}^{min}, N_M^{min}, N_S^{min} and N_{sp1}^{min}.

The values of the minimum heat loads of the utilities to be applied, optimum for energy costs, can de determined by several methods. In the case of multiple utilities and/or forbidden matches, the approaches given in[7,8,9,10] are adequate.

The minimum number of matches N_M^{min} is easy to calculate from eq. (9) of *Linnhoff* and *Hindmarsh*[11] or from eq. (10) of *Grimes* et al.[12].

$$N_M^{min} = \sum_{k=1}^{N_{k+1}} \left[N_{MT}^{min}\right]_k \tag{9}$$

$$N_M^{min} = N_{MT}^{min} + \sum_{k=1}^{N_k} \left[N_{HC_k} + N_{CC_k} - 1\right] \tag{10}$$

where: N_{CC_k}, N_{HC_k} – number of cold and hot pinch-crossing streams, respectively (see also work[14])

Parameter N_{MT}^{min} in the above formulae signifies the total minimum number for tree-type networks-see eq. (11). Subscript k in eq. (9) refers to the number of a subtask whereas k in eq. (10) refers to the number of a pinch.

$$N_{MT}^{min} = N_H + N_C + N_{HU} + N_{CU} - N_L \tag{11}$$

where: N_L – number of separate subtrees; $N_L = 1$ in eqs (9), (10)

It is possible to reduce N_M below N_M^{min} from eq.(9) or eq. (10) by using the so called pinch-crossing matches (see e.g.[13,14]).

These matches require, however, many shells and even the use of counter-current units; since heat capacity flow rates of streams have to be equal → $R = 1.0$ and for $F_t^{min} = 0.8$ ratio $\Delta T_h/\Delta T^{min}$ has to be less than 0.5 to use one shell. The use of the double temperature approach in the synthesis offers also a possibility of reducing N_M^{min} from eqs (9), (10), see e.g. work[5]. For targeting purposes, however, the use of formula (9) or (10) seems quite reasonable.

The method of predicting A_o^{min} (*Townsend* and *Linnhoff*[6]) is based on vertical matching of pieces of composite curves. The approach is valid for uniform heat transfer coefficients of streams and the exactness depends also on the sizes of enthalpy intervals (see[15]). The accuracy of calculations is sufficient for targeting, provided that heat transfer coefficients do not differ much. Having determined N_M^{min} and A_{o1}^{min}, it is possible to assess $\overline{C}_{a_1}$ from eq. (6). Since A_{o1}^{min} is valid for single tube pass apparatus and formula (6) does not account for multi-shell units, the result has to be correct for counter-current units.

To show this, we will introduce the example of *Floudas* et al.[16], who calculated for the task a dependence of the value of E for optimal solutions of their synthesis approach on ΔT^{min} (investment cost has been calculated for counter-current units). Data for example 1 as well as cost parameters are shown in Table 1. Table 2 shows a comparison of the cost computed by *Floudas* et al.[16] with the values of $\overline{E}$ and $\overline{C}_{a1}$ for counter-current apparatus. It is easy to note that eqs (6) and (8) meet the major requirement for substitute criteria - they order the solutions in the same way as the goal functions for E and C_a and strict optimization do. The relatively large difference between C_{a_1} and $\overline{C}_{a_1}$ is, most likely, due to a non-optimality of solutions from the *Floudas* et al.[16] approach. *Gundersen* and *Grossman*[17] noted that Floudas' method may give networks with large values of overall area A_o.

In the case of multi-pass apparatus, the necessity of applying eq.(7) is evident. Therefore, it is

Table – *Data for example 1 (from Floudas et al*[16]*.*

Stream	T_1 / K	T_2 /K	$G\,c_p$ / kW K^{-1}
h_1	630.555	338.888	7.913
h_2	583.333	505.555	5.803
h_3	555.555	319.444	2.374
h_4	494.444	447.222	31.652
h_5	477.777	311.111	6.3305
h_6	422.222	383.333	65.943
c	288.888	650.000	24.795
cu	300.000	333.333	–

Cost parameters:
p_{hu} = \$174.022/kW; p_{cu} = \$5.149/kg
$b = 0.6$; $a = 1300$; d = 0
cost of furnace = $0.45754\ Q^{0.7}$(\$ a^{-1}); Q in W
$E_{cu} = G_{cu} \cdot \rho_{cu} \cdot \Theta$
where: Θ – annual operation time

Table 2 – *The comparison of selected targets for example 1 - capital cost calculated for countercurrent apparatus*

ΔT^{min}/K	E_u, \$/a^{-1}	*C_{a_1},\$a^{-1}	$\overline{C}_{a_1}$,\$a^{-1}	**E,\$a^{-1}	$\overline{E}$,\$a^{-1}
24.0	495172.2	–	123911.6	–	619083.2
11.11	436900.0	217650	147320.3	654550.0	584220.3
6.38	415950.0	231100	161371.2	*647050.0	577321.3
5.55	412270.0	241130	169573.6	653400.0	581843.6

* *Dolan* et al.[27] gave the corrected value \$ 645695 per annum, we recalculated the area A_{o1} for the solution presented in fig.15 in[16] and found that it is incorrect - the corrected value of A_{o1} is 845.5 m^2. The network computed by SYNHEN shown in fig.1 has A_{o1} equal 787.3 m^2.

** the values from[16]

necessary to calculate A_{02}^{min} and N_S^{min} targets. The latter can be determined from the graphical approach of *Trivedi* et al.[18] or by the method suggested in the work of *Ahmad* and *Smith*[4]. The former approach yields values that are too low, esp. for tight composite curves (see *Ahmad* and *Smith*[4]) while the latter gives quite accurate predictions (though sometimes conservative) for all classes of problems. *Ahmad* and *Smith*[4] applied the number of shells from their approach to assess F_t factors for the mean temperature approaches MTD-s. Then, they included these F_t factors into the *Townsend* and *Linnhoff* model[6] for A_o^{min}. It is also possible to compute F_t factors in the "traditional" way, that is to apply the following algorithm to each enthalpy interval:

1. calculate F_t factor for $N_S = 1$ and 1–2 apparatus,
2. if F_t is less than prescribed F_t^{min} increase N_S by 1 and repeat calculation of F_t.

Our computations proved that F_t values from this method are the same as those calculated by the approach of *Ahmad* and *Smith*[4] (for identical F_t^{min} values).

In Table 3, we gathered the values of network costs for example 1 determined from eqs (7), (8) where N_S^{min} were calculated by the *Ahmad* and *Smith*[4] method. These costs are compared with the costs of networks synthesized by the package of computer programs called "SYNHEN" (the methodology on which SYNHEN is based is described in[19]). Comparison shows very good agreement between predictions from targeting and solutions from SYNHEN. This conclusion is also supported by the results published in[4], as well as by our computations for other tasks (omitted here for the sake of brevity). The very good accuracy of this targeting method for multi-shell apparatus can be explained as follows:

1. A_{o1}^{min} target from the model of *Townsend* and *Linnhoff*[6] and A_{o2}^{min} target from the *Ahmad* and *Smith*[4] approach are rather strict lower bounds that can be reached in many cases by "spaghetti" structures only;
2. N_S^{min} target from *Ahmad* and *Smith*[4] approach is usually too high;
3. substitute functions (6) and (7) assume even distribution of unit areas which then yield conservative predictions.

These three factors yield altogether a good approximation of HEN costs.

Values of E and $\overline{E}$ in Table 3 have been calculated without the cost of splits. There is no reliable method to date for predicting N_{spl}^{min}. It seems that in most cases necessary splits are only those at pinches; therefore, the rules from the PDM of *Linnhoff* and *Hindmarsh*[11] can be applied to assess N_{spl}^{min}. Some splits at pinches can be eliminated by the use of the dual temperature approach (see e.g.[5])

Table 3 – *The comparison of selected targets for example 1 - capital cost calculated for 1–2 units*

Target	ΔT^{min}=24.0 K	ΔT^{min}=11.11 K	ΔT^{min}=6.38 K
A_{o2}/m^2	399.3 443.0	552.5 662.6	688.6 855.5
N_S	16 15	25 23	29 26
C_{a_2} / \$$a^{-1}$	143264.07 144686.9	207288.74 217382.0	251582.92 261477.7
E/\$ a^{-1}	**6385435.6** **639589.1**	644188.74 1 654282.0	667532.92 677427.7

but, on the other hand, the PDM rules do not account for splits away from pinches.

Concluding, it is possible to state that the current methods made it possible to calculate targets: $Q_{hu,m}^{min}$ $(m=1,...,N_{HU})$, $Q_{cu,n}^{min}$ $(n=1,...,N_{CU})$, A_{o1}^{min}, A_{o2}^{min}, N_M^{min}, $N_S{}^{min}$ and N_{spl}^{min} and these targets applied to substitute functions (6), (7) and (8) yield proper predictions for HEN costs.

Use of targets to determine the values of decision variables before synthesis

Targets are actually applied to determining the proper value of the minimum temperature approach ΔT^{min} before synthesis (see e.g.[1,2,3,4]). It is, however, necessary to note that ΔT^{min} is not a unique parameter. To account for heat exchanger costs, it may be often necessary to use stream dependent ΔT^{min}, i.e. $\Delta T(h_i)^{min}$, $\Delta T(c_j)^{min}$ and $\Delta T(h_i c_j)^{min}$:

$$\Delta T(h_i,c_j)^{min} = \Delta t(h_i)^{min} + \Delta T(c_j)^{min} \qquad (12)$$

Fraser[20,21] suggested the use of the minimum heat flux Q''_{min} to obtain the single decision variable.

$$Q''_{min} = \alpha_s \cdot \Delta\, t^{min}\,(s,\,s) \qquad (13)$$

where: s refer to both hot and cold stream

The suggestion seems reasonable, but it should be tested for industrial problems. Certain authors, e.g.[5,22,23], introduced a dual temperature approach i.e. two temperature approaches: HRAT - to determine heat recovery and EMAT - to calculate heat exchangers.

Gundersen and *Grossmann*[17] proved, however, that EMAT is not a proper optimization parameter in their computerized synthesis method. It can be shown[24] that EMAT is really not a correct decision variable in any "intelligent" synthesis approach. In the following, we will use the minimum temperature approach ΔT^{min} which is equivalent to HRAT.

The other parameters that should be treated as decision variables for synthesis are the types and heat loads of the utilities. It is usually assumed even in the case of a single heating utility (hu) and a single cooling utility (cu) that the design is to be carried out for their minimum heat loads: Q_{hu}^{min} and Q_{cu}^{min}. In doing so, one assumes the hierarchy of costs; energy cost is more important than the investment one. We will show that an increase of the utility usage may reduce capital cost so that the overall expenses E are reduced.

In an industrial scenario, there are often multiple utilities to be potentially applied: LP steam, HP steam, exhaust gases, cooling water, brine and so on (see e.g.[25]). One can expect that the maximum use of the least costly utilities is the cheapest solution, but it can lead to an increase of investment as well as overall costs. Therefore, in a pre-design stage, it is necessary to determine the values of ΔT^{min} and the types and heat loads of utilities. Employing the optimization method seems superfloous since in practice one knows the set of available utilities and their parameters. Moreover, the values of utility heat loads depend on the ΔT^{min} value and, thus, they can be optimized in an internal loop. We suggest here the application of a simple algorithm that employs the intelligence and problem insight of a designer. The designer's task is to generate the values of variables, to analyze the results of targeting and to decide when to stop computations, i.e. to decide if the values of decision parameters are "good". The designer is aided by a computer program which computes targets:

A_{o1}^{min}, A_{o2}^{min}, N_M^{min}, N_S^{min}, N_{spl}^{min} and costs $\overline{C}_a$, $\overline{E}_u$ and $\overline{E}$. This program, named TARGETS, draws also composite curves and the plot $\Delta T = f(T_c)$.

The general methodology for targeting is as follows:

1. assumption of ΔT^{min} value
2. computation of targets and costs for "standard utilities"* (TARGETS)
3. analysis of results, data of utilities
4. computation of targets and costs (TARGETS)
5. analysis of results, decision whether to redu-ce heat recovery level or the usage of some utilities, if yes, go to step 4, if no, to step 6**
6. decision whether to change ΔT^{min}, if yes, go to 1, if no, stop calculations.

The choice of utilities whose usage will be decreased is undertaken on the basis of composite curves analysis. In general, the use of those utilities that cause a wider gap between the composite curves should be increased. The approach for determining $Q_{hu}{}^{min}$ and $Q_{cu}{}^{min}$ suggested in[10] gives also an easy insight into a task. Finally, the results from the PTA[26] can be also applied to aid such a decision (see example 3).

The following methods are applied in TARGETS to calculate the targets:

1. $Q_{hu,m}^{min}$ $(m=1,...,N_{HU})$, $Q_{cu,n}^{min}$ $(n=1,...,N_{CU})$ are determined by the approach described in[10] since it gives an easy insight into a task,

2. A_{o1}^{min} is calculated by the method of *Townsend* and *Linnhoff*[6] and A_{o2}^{min} from the *Ahmad* and *Smith*[4] approach. The difference is that in TARGETS smaller enthalpy intervals are used than those applied in works[1,2,3,6].

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*By standard heating utility we mean the one that has the highest temperature and by standard cooling utility the one that has the lowest; they are usually the most costly media. The results of heat recovery calculations for these utilities give a proper insight into a task to help the designer to decide which utilities should be taken into account. An example is given by *Jezowski* and *Friedler*[10] to illustrate such an analysis.

**For multiple utilities, a two level approach is suggested:

a) reducing the use of selected utilities while keeping Q_u at the minimum,

b) reducing the heat recovery level.

Table 4 – *The comparison of selected targets for example 1 - heat recovery level decreased by 0.9*

ΔT^{min}	N_S^{min}	A_{o2}^{min}/m^2	$\bar{E}_u^{min}$/\$ a^{-1}	$\bar{C}_{a_2}$/,\$ a^{-1}	$\bar{E}$/ \$ a^{-1}
24.0	15	336.39	544689.4	132501.3	677190.71
11.11	19	430.45	481649.89	166555.5	648205.44
6.38	18	495.91	458583.94	176854.11	635438.05

The network computed by SYNHEN for ΔT^{min} = 6.38 K has the following parameters:
$N_S = 24$, $A_{o2} = 599.6\ m^2$, C_{a2} = \$ 209644.9 a^{-1}, E = \$ 668228.6 a^{-1}

3. N_M^{min} is rated from eq. (9)

4. N_S^{min} is computed according to the method given by *Ahmad* and *Smith*[4]

5. N_{spl}^{min} is assessed from the PDM[11] rules.

It is worthwhile noting that the TARGETS program can be used for tasks with temperature dependent enthalpies of streams, for instance enthalpy changes of streams for examples 2 and 3 in this work (Tables 5,7) have been calculated from eq. (14) according to *Berghoff*[28].

$$\Delta H = \int_{T^1}^{T^2} \left[\frac{1{,}6845}{\sqrt{d}} K_1 + \frac{0{,}03762}{\sqrt{d}} K_1 t \right] dt \quad (14)$$

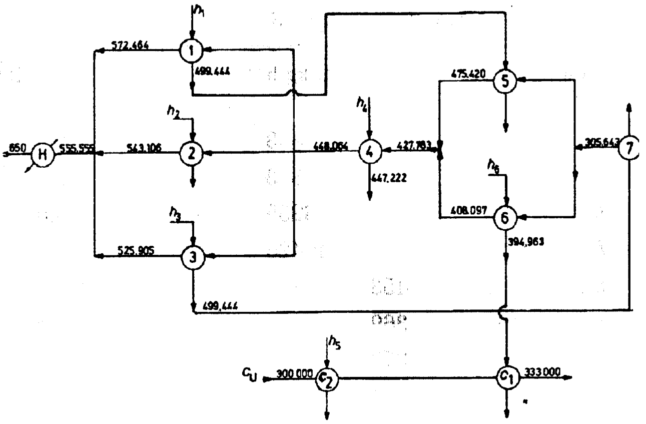
where: T – in °C

d – relative density of a stream

K_1 – Watson factor for oil fraction

Examples

For example 1, we will show the effect of decreasing heat recovery level on the overall cost in the case of a single heating and a single cooling utility. The results of targeting gathered in Table 5 show that by increasing Q_{hu}^{min} and Q_{cu}^{min} by 1.1, one can obtain cheaper solutions for ΔT^{min}=11.1 and 6.38K than for the maximum heat recovery. The higher effect of heat recovery reduction is noted in example 2 - the industrial problem from crude oil atmospheric and reduced pressure distillation (data in Table 5). Increasing Q_{hu}^{min} in a furnace and the heat load of cooling water by 1.1 causes reduction of the total cost of a HEN, giving also a simpler HEN structure (Table 6).



F i g. 1 – *The optimal network synthesized by SYNHEN for example 1 – ΔT^{min} = 6.38 K*

T a b l e 5

stream	G/

T a b l e 6 – *The comparison of selected targets for example 2 – ΔT^{min} = 11.11 K*

Target	$Q_u = Q_u^{min}$	$Q_u = 1.1\ Q_u^{min}$
$\bar{E}_u$, \$ a^{-1}	1804910.8	1985402.0
A_{o2}^{min}/m^2	11275.5	8283.96
N_S^{min}	69	50
$\bar{C}_{a2}$, \$ a^{-1}	1983923.0	1433973.0
$\bar{E}$, \$ a^{-1}	3788833.8	3419375.0

The analysis of the composite curves for the above examples enables the designer to predict qualitatively the effect of reducing the heat recovery level. Fig. 2 shows the composite curves for example 1 with the maximum and reduced heat recovery levels, the composite curves for example 2 for the identical levels of heat recovery are presented in Fig.3. One can expect that the increase of the utility usage in example 2 will yield a more substantial effect than that for example 1. The former task is almost pinched in a wide temperature range of 450–550 K and after the increase of utility usage, there is a gap between composite curves.

Table 7 – *Data for example 3*

stream	T_1/ K	T_2/ K	G/kg h^{-1}	d	α/kW m^{-2}K^{-1}
h_1	598	505	27863	0.865	0.3055
h_2	596	492	58813	0.956	0.2778
h_3	553	453	293255	0.828	0.4167
h_4	518	317	40425	0.793	0.4167
h_5	505	453	27863	0.865	0.4167
h_6	492	369	158813	0.956	0.3055
h_7	417	379	453926	0.757	0.4167
c_1	288	394	375000	0.842	0.2778
c_2	394	633	375000	0.842	0.4167
c_u	283	323	–	1.000	2.333

Cost parameters the same as for example 1
Enthalpy changes calculated as for example 2

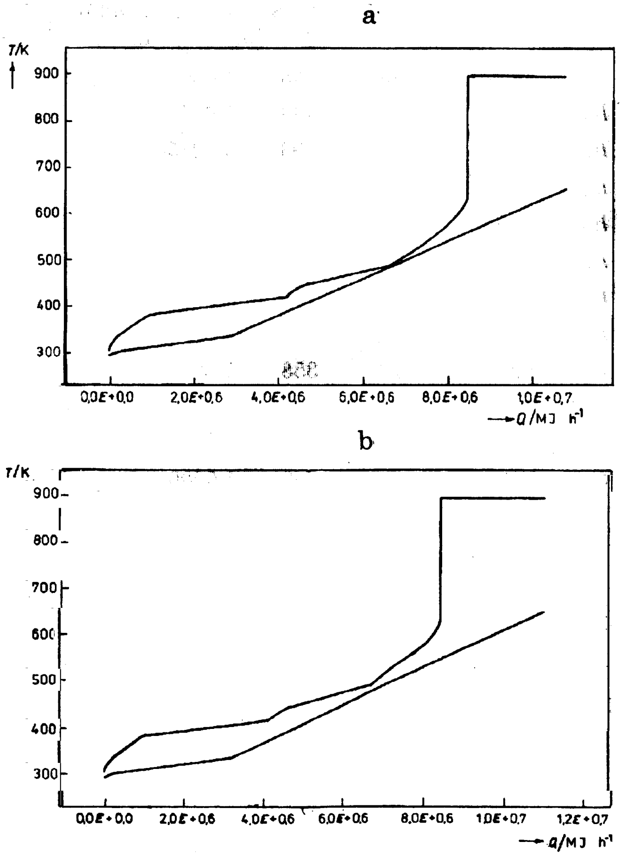


Fig. 2 – *Composite curves for example 1*
a. the maximum heat recovery
b. heat recovery reduced by 0.9

Table 8 – *The example of application of the PTA for the choice of utility types for example 3*

Temperature interval	Heat required MJ h^{-1}	Heat flow MJ h^{-1}
		95782.32 *
1. 633-598 K	55688.48	40093.84
2. 598-596 K	57856.22	37926.10
3. 596-553 K	**95782.32**	0.0
4. 553-518 K	94836.30	946.02
5. 518-505 K	92963.76	2818.50
6. 505-492 K	91122.50	4659.82
7. 492-417 K	90522.22	5260.10
8. 417-394 K	81893.94	13888.38
9. 394-333 K	92085.23	3697.07
10. 333-288 K	116495.80	(–20713.48 **)

* h_{u1} applied

** h_{u2} required

Example 3 is also an industrial problem from crude oil distillation (data in table 7). To heat up crude oil, the designer can use a furnace (in a region of high temperatures) and also another heating utility. It was shown by the authors in[10] that it is sufficient in this case to apply a low-grade heating utility. This conclusion can also be drawn by analyzing the results of the PTA calculations. Table 8 gives the values of heat loads that are needed in temperature intervals (that is, before applying the heating utility). It is easy to note that 958 GJ h^{-1} has to be supplied in the high temperature region (by the furnace). The values of heat loads which flow from one interval to the lower temperature interval after adding this amount of heat into the furnace are given in column 3 of Table 8. Additional heat load is required in the low

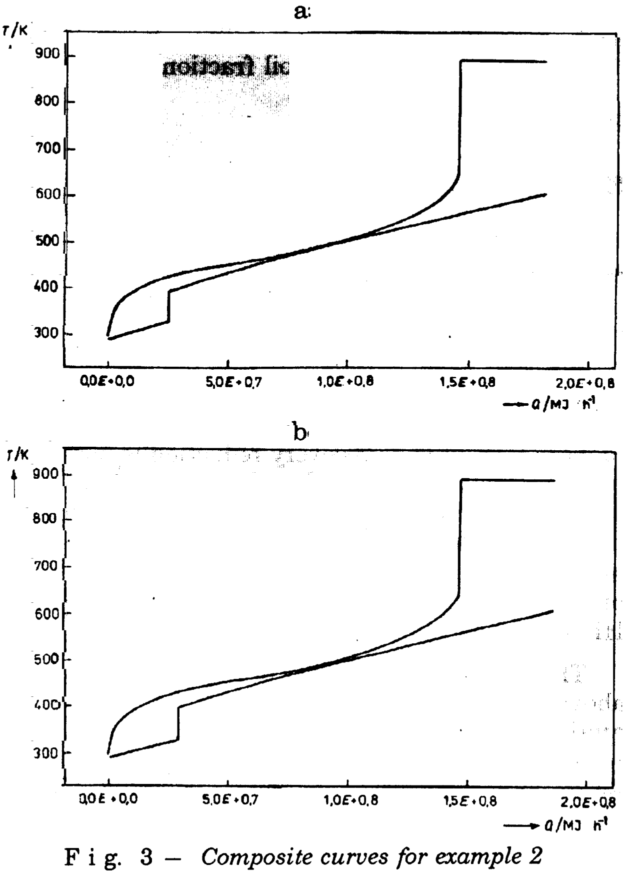


Fig. 3 – *Composite curves for example 2*
a. the maximum heat recovery
b. heat recovery reduced by 0.9

T a b l e 9 – *The comparison of the selected targets for example 3*

Q_{hu1}	$\bar{E}_u$/ \$ a^{-1}	A_{o2}^{min}/m^2	N_S^{min}	$\bar{C}_{a_2}$, \$ a^{-1}	$\bar{E}^{min}$, \$ a^{-1}
Q_{hu}^{min}	5631242.0	8210.5	14	916399.5	6547741.5
$1.02 \cdot Q_{hu1}^{min}$	4630064.6	20519.3	37	2253419.9	6883484.5
$1.06 \cdot Q_{hu1}^{min}$	4730192.0	17594.4	33	1928767.6	6658959.5
$1.086 \cdot Q_{hu1}^{min}$	5030632.7	12829.9	25	1450624.2	**6481256.9**

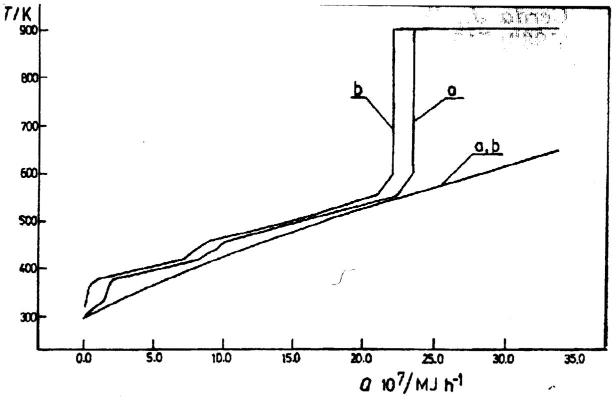
* For all cases the following condition was kept

$$Q_{hu1} + Q_{hu2} = Q_{hu}^{min}$$

thus the results in 1-st row refer to: $Q_{hu2} = 0$ and $Q_{hu1} = Q_{hu}^{min}$

temperature region, below 333 K. Thus, any low grade, cheap heating utility can be supplied e.g. cooling water which has been heated up in another subsystem. This heating utility (we assummed temperature range from 333.0 to 300.0 K) can be treated as a free utility. Therefore, the use of the maximum possible heat load of "heating" water seems to be the cheapest solution. For $\Delta T^{min} = 11.1$ K, this apparently evident assumption is incorrect. In Table 9, we gathered the values of the costs predicted from targets for the use of a furnace only and the use of both heating utilities while the heat load of heating water decreased from the maximum value. By the maximum load heat of the second utility we mean such a value for which the minimum heat of both utilities is reached or, equivalently, utilities of minimum cost are applied. The results of targeting show clearly that the use of maximum heat load of heating water will yield an expensive network with a complex structure. However, by decreasing water usage, the designer can improve the solutions.

Qualitatively, this effect can be predicted from the composite curves. Fig. 4 shows them for example 3 for the case when all the heat required is supplied in the furnace (row 1 in Table 9) and for the case when both utilities are used but the amount of heat supplied in the furnace is higher by 1.086 than the minimum heat that has to be supplied in the furnace.



F i g. 4 – *Composite curves for example 5*
a. total heat supplied in the furnace ($Q_{hu,1} = Q_{hu}^{min}$)
b. heat supplied in the furnace and by the ~~*heating water - heat in the furnace*~~
$Q_{hu,1} = 1.086 \cdot Q_{hu,1}^{min}$

Summary

The examples presented in the paper illustrate the necessity of treating heat loads of the utilities as the decision variables in HEN synthesis. They show that the traditional view, according to which the optimal solutions should feature the maximum energy recovery or the minimum cost of the utilities applied, is incorrect. It seems that in some cases, esp. for the tasks with tight composite curves, an increase of utilities usage or their cost (for multiple utilities) can yield a decrease of the total cost of a HEN. Choice of "good" values of the minimum temperature approach and heats of utilities can be easily made in the targeting stage prior to the synthesis. The simple algorithm for screening the proper values of ΔT^{min} and heat loads of the utilities is given in the paper. This algorithm, employing the current methods for calculating the targets for HEN, gives results precise enough for solving industrial problems.

S y m b o l s

a – parameter in eqs for investment cost of apparatus
A – heat transfer surface area, m^2
A_o – overall heat transfer surface area of a network, m^2
A_{o1}, A_{o2} – values of A_o for counter-current and multi-passes apparatus, respectively, m^2
b – parameter in eqs for investment cost of apparatus
c_j – j-th cold process stream
~~$c_{u,n}$ – n-th type of cooling utility~~
C_a – investment cost of a network, \$ a^{-1}

C_{a_1}, C_{a_2} – values of Ca for counter-current and mutipass apparatus, respectively, $\$ \ a^{-1}$
CC – composite curves
d – relative density of oil fraction in eq. (14)
E – overall cost of a network, $\$ \ a^{-1}$
E_u – overall cost of utilities applied, $\$ \ a^{-1}$
EMAT – (heat) exchanger minimum approach temperature, K
F_T – correction factor for logarithmic mean temperature difference
G – mass flow rate of a stream, kg h^{-1} (kg s^{-1})
$G \ c_p$ – heat capacity of a stream, kW K^{-1}
h_i – i-th hot process stream
$h_{u,m}$ – m-th type heating utility
HEN – heat exchanger network
HRAT – heat recovery approach temperature, K
H – enthalpy, kJ kg^{-1}
N_K – number of pinches in a task
K_1 – Watson factor for oil fraction (eq.14)
M – parameter in eq. for cost of piping and maintenance
N_A – number of apparatus in a network
N_{spl} – number of splits in a network
N_C – number of cold process streams
N_{CU} – number of cooling utility types available
N_H – number of hot process streams
N_{HU} – number of heating utility types available
N_M – number of matches in a network according to eqs (9) and (10)
N_{MT} – number of matches in a network from eq.(11)
N_S – number of shells
p – unit price of an utility, \$/kW a
PTA – the Problem Table Algorithm[26]
Q – heat, kW
Q_{cu}, Q_{hu} – heat load of heating and cooling utilities applied respectively, kW
Q_u – total heat load of heating and cooling utilities applied, kW
R – parameter for F_T calculation; $R = \Delta T_c / \Delta T_h$
Q''_{min} – minimum heat flux according to Fraser[20,21], kW m^2
SYNHEN – computer programs package for HEN synthesis
T – temperature, K
TARGETS – computer program for computing targets for HEN

Greek letters

α – heat transfer coefficient for a stream, kW m^{-2} K^{-1}
β, γ, Φ – parameters in eqs for cost of piping and maintanance
$\Delta T_c, \Delta T_h$ – temperature changes of cold and hot streams in a match, K
ΔT^{min} – minimum temperature approach (equivalent to HRAT), K
$\Delta T^{min}(h,c)$ – minimum temperature approach for a match between streams h and c,K
$\Delta T_c, \Delta T_h$ – temperature changes of cold and hot streams in a match, K

Subscripts

c,h – refers to cold, hot process stream, respectively
cu/hu – refers to cooling/heating utility, respectively
cu,n – refers to n-th type of cooling utility
hu,m – refers to m-th type of heating utility
u – refers to utilities

Superscripts

min – refers to the minimum value
1,2 – refers to inlet, outlet, respectively
– – refers to substitute kriteria

References

1. *Ahmad S., Linnhoff B.,* Overall cost targets for heat exchanger networks. IChemE Ann1 Res. Mtg, Bath (1984)
2. *Ahmad S., Linnhoff B.,* SUPERTARGET; optimisation of chemical solvents plant - different process structures for different economies. ASME Winter Mtg, Anaheim, California (1986)
3. *Linnhoff B., Ahmad S.,* J. Energy Res.Tech. **111** (1989) 131
4. *Ahmad S., Smith R.,* ICheM. Chem. Eng. Res. Des. **67** (1989) 481
5. *Trivedi K.K., O'Neill, B.K., Roach, J.R.,* Wood,R.M. Comput.chem.Engng. **13** (1989) 667
6. *Townsend D.W., Linnhoff B.,* Surface area targets for heat networks. IChemE Ann1 Res. Mtg., Bath (1984)
7. *Cerda J., Westerberg A.W.,* Chem.Eng.Sci. **38** (1983) 745
8. *Papoulias S.A., Grossmann I.E.,* Comput.chem. Engng. **7** (1983) 707
9. *Viswanathan M., Evans L.B.,* AIChE Jl **33** (1978) 1781
10. *Jezowski J., Friedler F.,* A simple approach for maximum energy recovery calculations to be submitted to Chem.Eng.Sci.
11. *Linnhoff B., Hindmarsh E.,* Chem.Eng.Sci. **38** (1983) 745
12. *Grimes L.E., Rychener M.D., Westerberg A.W.,* Chem.Engng.Commun. **14** (1982) 339
13. *Wood R.M., Wilcox R.J., Grossmann I.E.,* Chem. Engng.Commun. **39** (1985) 371
14. *Jezowski J.,* Chem.Eng.Sci. **45** (1990) 1928
15. *Saboo A.K., Morari M., Colberg R.D.,* Comput. chem.Engng. **10** (1986) 591
16. *Floudas A.C., Ciric A.R., Grossmann I.E.* AIChE Jl **32** (1986) 276

17. *Gundersen T., Grossmann I.E.,* Improved optimization strategies for automated heat exchanger network synthesis through physical insights. AIChE Annl Mtg 1988
18. Trivedi K.K., Roach J.R., O'Neill B.K., AIChE Jl **33** (1987) 2087
19. *Jezowski J.,* Linear programming based method of heat exchanger network synthesis. to be published in Inž.Chem.Proc. 1990
20. *Fraser D.M.,* Chem.Eng.Sci. **44** (1989) 1121
21. *Fraser D.M.,* The application of minimum flux specification to the design of heat exchanger networks. Dechema Monographs vol.116, pp.256-261.Comput.Appl.Chem.Engng.Proc.Europ.Symp., Erlangen 1989
22. *Challand T. B., Colbert R.W., Venkatesh C.K.,* Chem. Engng.Prog. **77** (1981) 65
23. *Colbert R.W.,* Chem.Engng.Prog. **78** (1982) 47
24. *Jezowski J.,* A note on dual temperature approach for heat exchanger network synthesis. to be published in to Comput.chem.Engng.
25. *Linnhoff B., Lenz W.,* Chem. -Ing.-Tech. **59** (1987) 851
26. *Linnhoff B., Flower J.R.,* AIChE Jl **24** (1978) 633
27. *Dolan W.B.; Cummings P.T.; LeVan M.D.* AIChE Jl **35** (1989) 725
28. *Berghoff W.,* Erdolverarbereitung und Petrolchemie - Taffeln und Tabellen, VEB Leipzig 1968 (in German)