Synthesis of Heat Exchanger Networks ï Smart optimisation procedures

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Synthesis of heat exchanger networks is still a challenging task. Pinch technology, apart from the analysis itself, has also established a number of fundamental rules for design of the heat exchanger network to accomplish the energy targets. These rules, however, are not always conclusive especially in case of stream splits and although the results can meet the energy targets, said results are not always optimal in terms of overall cost.

A few alternative procedures will be discussed hereafter and illustrated by the application on a 4 streams example originally proposed by Shenoy [1]. The example has 2 hot steams, 2 cold streams, a hot and a cold utility; the data set is given in Table 1.

Table 1: Data set example.

Tsupply °C	Ttarget °C	Heat kW	DT-Shift K	U*f kW/K,m²	Descript -
175	45	1300	6.5	0.2	H1
125	65	2400	6.5	0.2	H2
20	155	2700	6.5	0.2	C1
40	112	1080	6.5	0.2	C2
180	179	360		0.2	Heating
15	25	280		0.2	Cooling

Cost data

Heating : 120 \$/kW,year Cooling : 10 \$/kW,year

Area Cost (\$) = 30000 + 750 x Area $^{0.81}$ Annual cost factor = 0.3221

Annual Area Cost (\$/year) = 9663 + 241.575 x Area $^{0.81}$

Energy consumption in the table corresponds with an overall DTMin of 13 K. Composite curves are shown in Figure 1.

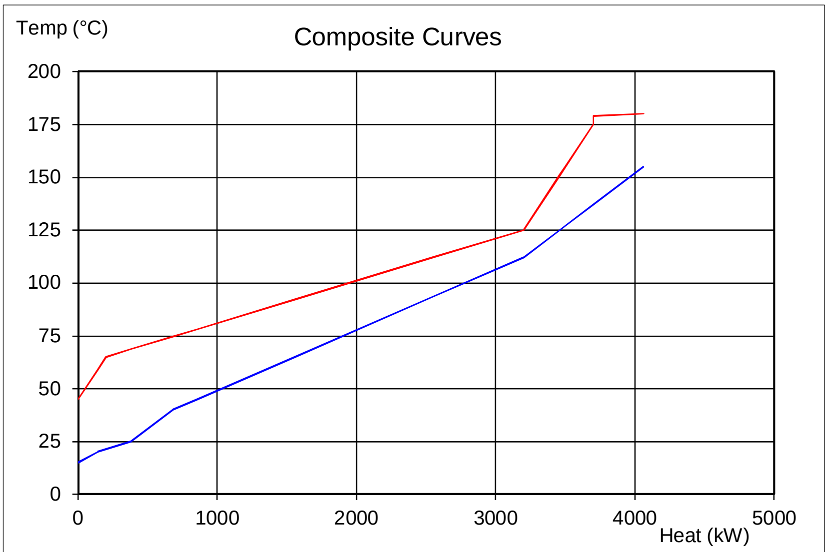

Figure 1: Composite Curves.

The annual cost factor A_f was calculated according to the formula $A_f = (1+i)^n/n$ whereas i is the interest rate (10%) and n is the project life time (5 years). It should be understood that this annual cost factor is arbitrary and does not correspond to the annuity of the investment required to generate a Net Present Value equal to that investment. Since, however, said cost data have been used in the scientific publications, they have been withheld for further comparison.

Trade-off in classic pinch analysis is done on the basis on a uniform DTMin with a segregation of the problem above and below the pinch. Here, trade-off is done on the basis of the heat load, once with segregation at the pinch and once without such segregation, assuming one single system. The results, shown in Figure 2, give a total cost target of 239,450 \$/year for a heating load of 360 kW and a network with 6 units (2 systems) and a total cost target of 226,111 \$/year for a single system with 5 units, also for a heating load of 360 kW.

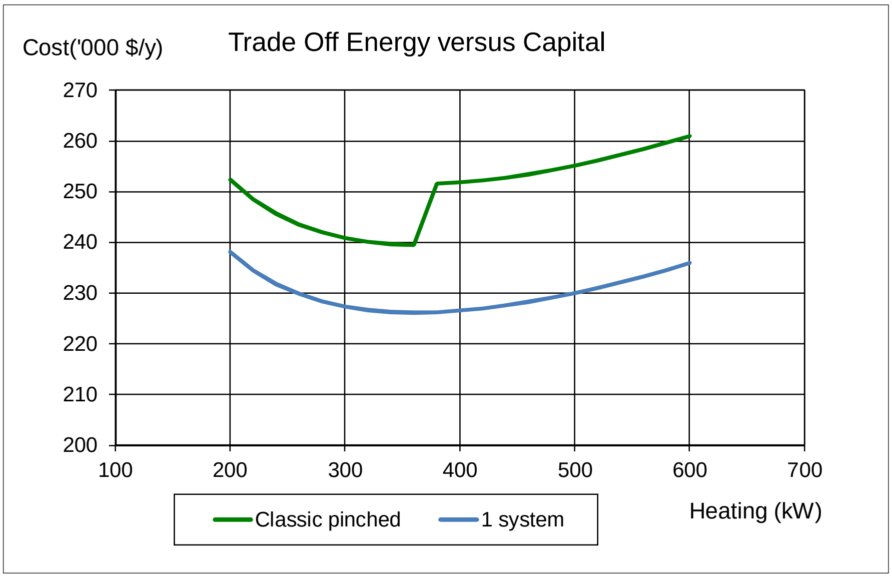

Figure 2: Trade-off energy versus capital as a function of the heating load.

The results developed by Shenoy are shown in Table 2, which has been completed with results obtained after further optimisation of the networks by incremental evolution.

Table 2: Results as reported by Shenoy and after optimisation by incremental evolution.

Results pinch design	Reported				Optimised			
	Heating	# units	# splits	Cost	Heating	# units	# splits	Cost
Alternative	kW	-	-	\$/year	kW	-	-	\$/year
S1	360.0	6	1	245,828	371.9	6	1	242,336
S2	360.0	6	1	248,238	388.2	6	1	241,849
S3	360.0	6	2	240,025	353.3	6	2	238,173
S4	360.0	6	2	261,423	384.7	6	2	251,218

The optimised networks of Table 2 are shown in Figure 3. They can be further improved by application of specific procedures as explained and illustrated hereafter. Alternatively, instead of following the pinch design rules directly, heuristics can be used whilst taking into account the insight gained from pinch technology.

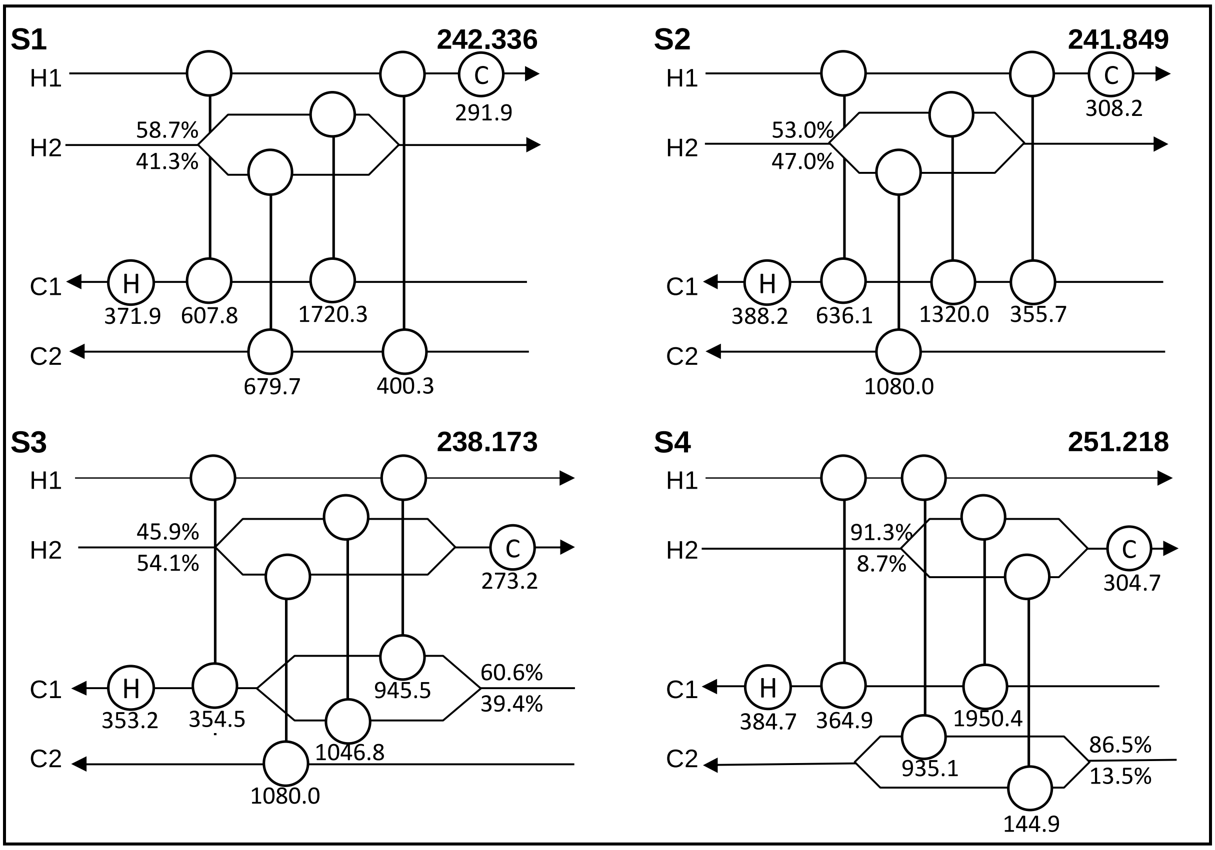

Figure 3: Optimised networks of Table 2.

Heuristics.

A network with minimum cost can be generated with a smart tick-off procedure respecting the following rules and optimising the network so obtained:

- Rule 1: satisfy the smallest heat load with one unit;
- Rule 2: match a stream stretching over the pinch with a (branch of a) counterpart also stretching over the pinch;
- Rule 3: no heating below the pinch, no cooling above the pinch, no heat transfer across the pinch.

The procedure leads to the following matches:

- C2 on a branch H2b of H2 (rules 1 and 3);
- H1 on a branch C1a of C1 (rules 1 and 2);
- Cooler on the cold side of branch H2a;
- Heater on the hot side of branch C1b (rule 3);
- Fill in the remaining match H2a ï C1b.

The result is a network with 5 units and 2 splits with a cost of 230,549 $/year, evolving to 227,544 $/year after further optimisation by incremental evolution. Relocation of the cooler from branch H2a to branch H2b and further optimisation leads to a minimum cost network with a heating load of 384.7 kW, 5 units, 2 splits and a cost of 226,721 $/year, which is within 0.27% of the target. This network, shown in the overview in Figure 9 reference Alt.8b can also be developed by automated procedures.

Automated procedures.

Several alternative networks can be developed by using simple automated procedures. The grid from the analysis contains 7 bands (superstructures) of which bands 5, 6 and 7 can be merged (Table 3).

Table 3: Stream Grid diagram reduced to 5 bands.

Tsupply	Ttarget	Heat	Descript.	mcp	Bands & temperatures (°C)					
°C	°C	kW	-	kW/K	1	2	3	4	5	
180	179	360	Heating	360	180.0	179.0				
175	45	1300	H1	10		175.0	125.0	74.6	68.6	45.0
125	65	2400	H2	40			125.0	74.6	68.6	65.0
20	155	2700	C1	20	155.0	137.0	112.0	40.0	25.0	20.0
40	112	1080	C2	15			112.0	40.0		
15	25	280	Cooling	28					25.0	15.0

The following network alternatives can be generated using Linear Programming (LP):

- Alt.1: starting with the 5 bands, merging bands 3 and 4 (Table 4) and applying LP;
- Alt.2: as Alt.1 with forbidden match between H1 and C2, so avoiding a split on cold stream C2.

In both cases, after optimisation, the cooling duty will be concentrated on hot stream H1.

Table 4: Stream Grid diagram reduced to 4 bands (Alt.1and Alt.2).

Tsupply	Ttarget	Heat	Descript.	mcp	Bands				
°C	°C	kW	-	kW/K	1	2	3	4	
180	179	360	Heating	360	180.0	179.0			
175	45	1300	H1	10		175.0	125.0	68.6	45.0
125	65	2400	H2	40			125.0	68.6	65.0
20	155	2700	C1	20	155.0	137.0	112.0	25.0	20.0
40	112	1080	C2	15			112.0	40.0	
15	25	280	Cooling	28				25.0	15.0

Starting with the 5 bands, also bands 4 and 5 can be merged (Table 5). In that case, the cooling duty can be imposed on hot stream H2. This would lead to:

- Alt.3: applying LP with forbidden match between H1 and Cooling;
- Alt.4: as Alt.3 with forbidden match between H1 and C2, so avoiding a split on cold stream C2.

Table 5: Stream Grid diagram reduced to 4 bands (Alt.3 and Alt.4).

Tsupply	Ttarget	Heat	Descript.	mcp	Bands				
°C	°C	kW	-	kW/K	1	2	3	4	
180	179	360	Heating	360	180.0	179.0			
175	45	1300	H1	10		175.0	125.0	74.6	45.0
125	65	2400	H2	40			125.0	74.6	65.0
20	155	2700	C1	20	155.0	137.0	112.0	40.0	20.0
40	112	1080	C2	15			112.0	40.0	
15	25	280	Cooling	28				25.0	15.0

The initial networks are shown in Figure 4.

With LP applied to four integration bands, a minimum number of units is obtained within each band; consequently, the total number of units (8) is higher than in a pinch design (6).

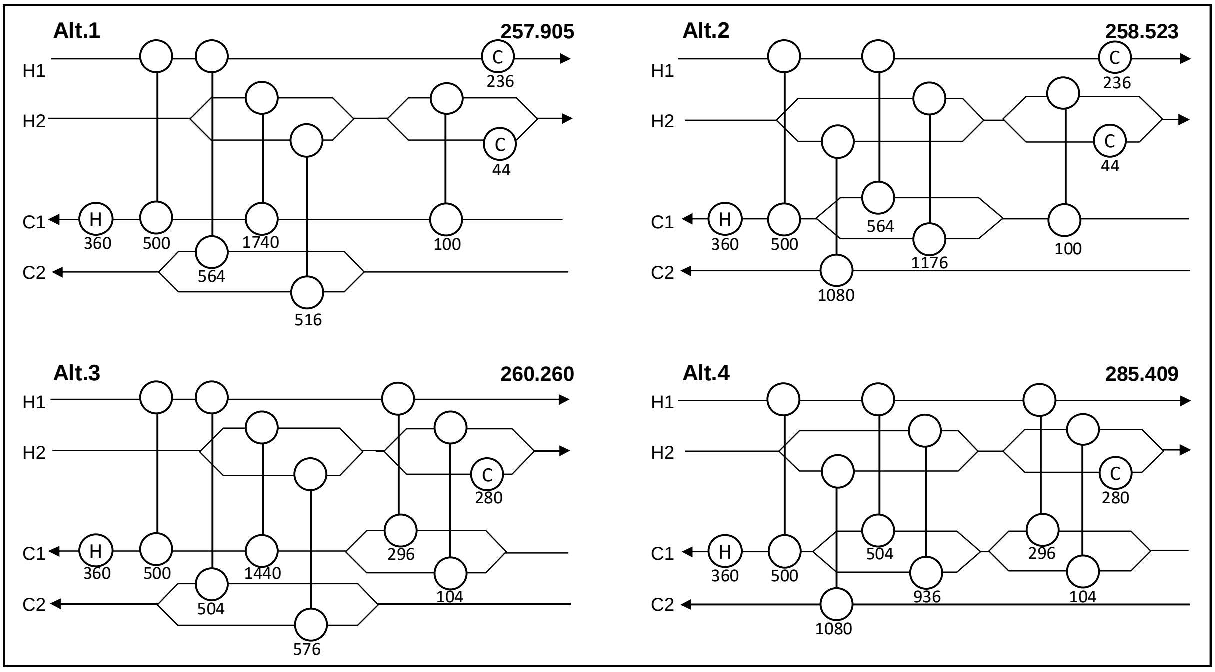

Figure 4: Initial networks for alternatives Alt.1 to Alt.4.

For the 4 given alternatives, the number of bands of the grid can be reduced from 4 to 3 by merging bands 1 and 2, putting the heater and the first exchanger on cold stream C1 in parallel, resulting respectively in alternatives Alt.5 to Alt.8.

The initial networks can be optimised by incremental evolution and simplified by distortion of the solution space and nodes between consecutive split configurations can be refined by smart node arrangements. The procedures are explained hereafter.

a) Incremental evolution.

For an initial network that contains a path between a heater and a cooler, a trade-off between energy and capital can be made by adjusting the load on the heater whilst establishing and maintaining the heat balance over the path. The number of variables (degrees of freedom) equals the number of paths. Also in case of loops in the network, the heat loads of the units in a loop can be adjusted whilst maintaining the heat balance in the loop. The number of variables (degrees of freedom) equals the number of loops. Depending upon the cost structures, this trade-offs might lead to simplification of the network and reduction of the number of units.

b) Distortion of the solution space.

If the cost structure has the form $C = A + B \times Area^{C}$, then for a network that contains more heat exchanger units than the minimum there is a potential for reducing that number which might lead to further reduction of the total cost. The cost function favours unequal unit areas and this effect is stronger with lower values of the exponent c; a lower value will tend to kick out the smaller units. This is illustrated for the pinch design network S3 after optimisation by incremental evolution (Figure 5a). In the normal case, during incremental evolution of the unit A1, the solution is trapped in the minimum of the trough of the red cost curve (a sub-optimum) as shown in Figure 6. Reduction of the exponent c from 0.81 to e.g. 0.4 will pull down and distort the solution space. After pull-down, application of incremental evolution at constant heating will let the previous solution run further down out of the original trough into a new trough without the exchanger A1. This is shown in the blue curve in Figure 6, where for reason of comparison the fix cost has been increased to obtain the same total cost as for the normal case for the given heating load.

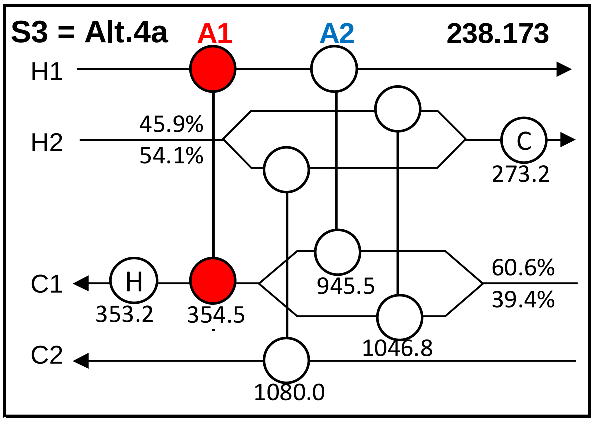

Figure 5a: Network before pull-down

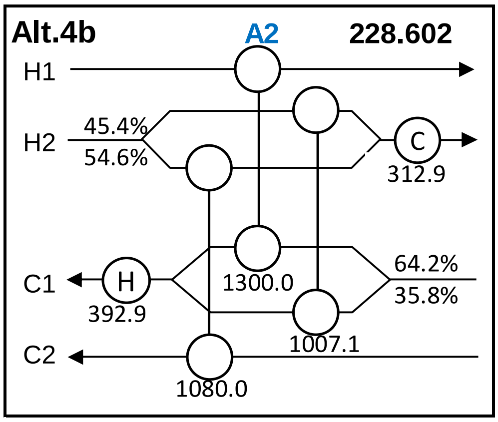

Figure 5b: Network after pull-down

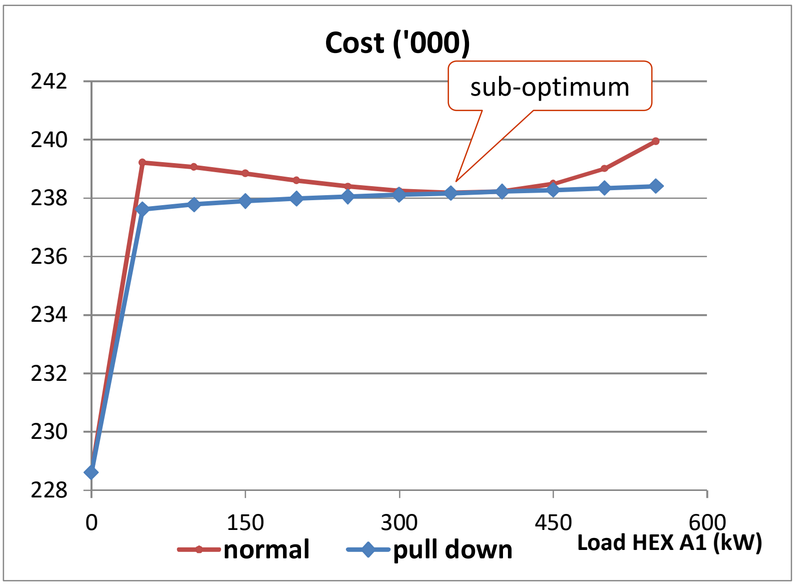

Figure 6: Cost evolution in the normal case and the pulled-down case.

The solution space can now be restored by going back to the original value for the exponent c and incremental evolution, now at variable heating, will generate a new optimum with one heat exchanger unit less as shown in Figure 5b (the load of unit A1 has been merged into unit A2.

Instead of being pulled-down, the solution space can also be pushed up by increasing the value c to 1; incremental evolution at variable heating might push the solution into an adjacent trough and after restoring the solution space, this configuration can be used as starting point for a new optimisation or for a new pull-down and incremental evolution at constant heating.

c) Smart node. .

A node between consecutive split configurations can be refined by a smart node arrangement as shown in Figure 7 (A: standard node, B: smart node, C: double smart node). Smart nodes enable the merger of 2 heat exchangers that are on the same stream branches in adjacent integration bands and other arrangements as shown further in the examples.

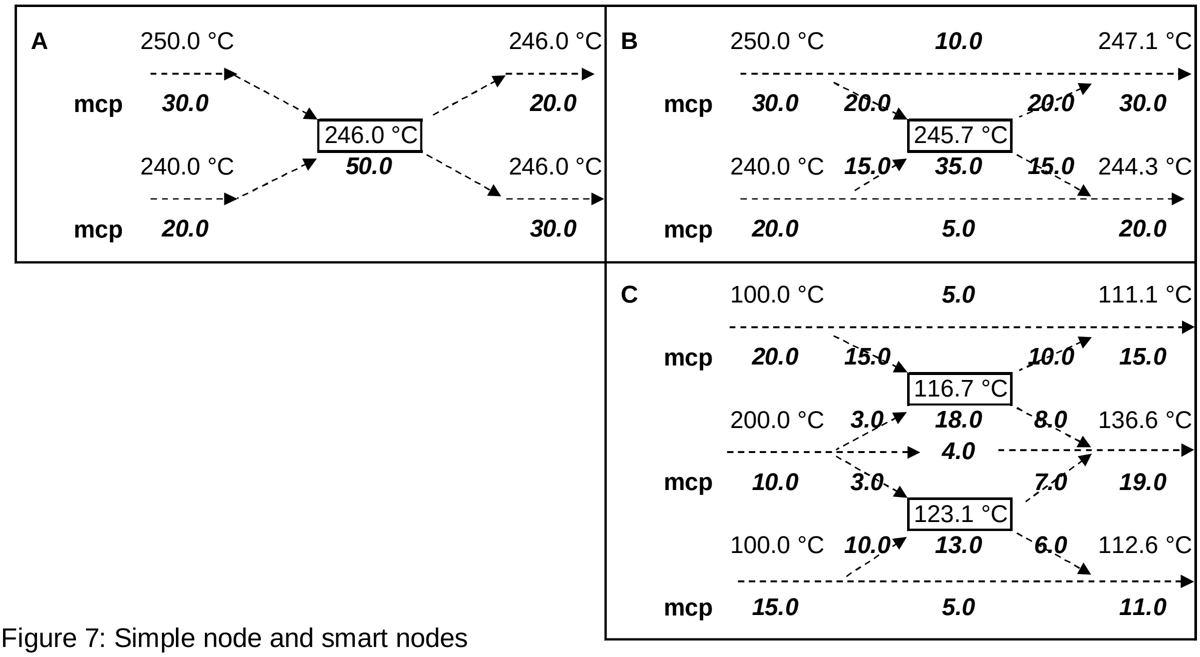

Figure 7: Simple node and smart nodes

The 3 bands grid can be reduced to 2 by merging bands 2 and 3. The resulting networks develop into alternatives already generated by the procedures mentioned earlier. A particular network with a double split on hot stream H2 in band 2 is shown in Figure 8; this network can successfully be developed into the network alternative Alt.8b using smart node configurations.

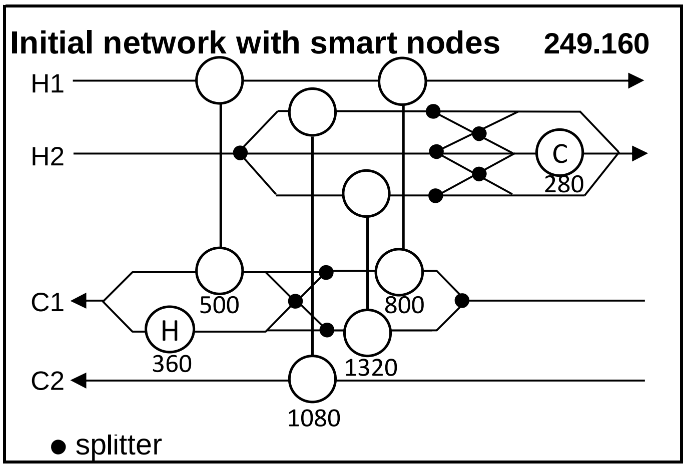

Figure 8: Example of an initial network for 2 integration bands with simple and smart nodes.

The results of application of the various procedures are summarised in Table 6; related networks are shown in Figure 9.

The procedures described combine relaxation techniques of classic pinch technology and capabilities of Mixed Integer Non Linear Programming (MINLP) for simplification of networks.

Table 6: Optimised networks.

LP 4 bands	Initial network				Optimised				
	Heating	# units	# splits	Cost	Heating	# units	# splits	Cost	
Alternative	kW	-	-	$/year	kW	-	-	$/year	
Alt.1	360.0	8	3	257,905	341.8	6	2	234,344	1.a
distortion °4)					732.1	5	2	260,864	1.b
distortion °5)					730.2	5	0	253,384	1.c
distortion °6)					513.0	5	0	244,616	1.d
Alt.2	360.0	8	3	258,523	335.4	6	2	236,423	2.a
distortion °2)					421.7	5	2	239,066	2.b
distortion °4), °7)					565.9	5	1	239,796	2.c
distortion °5)					565.9	5	0	241,922	2.d
Alt.3	360.0	8	4	260,260	334.4	7	2	247,711	3.a
distortion °2)					384.7	6	2	251,218	3.b
distortion °3)					513.0	5	0	244,616	3.c =1.d
distortion °6)					732.6	5	0	255,118	3.d
Alt.4 Simple node	360.0	8	4	261,250	353.2	6	2	238,173	4.a
distortion °2)					392.8	5	2	228,602	4.b
Alt.4 Smart node					353.5	6	2	238,057	4.c
distortion °2)					393.6	5	2	228,563	4.d
LP 3 bands									
Alt.5	360.0	8	5	263,184	348.8	6	3	237,130	5.a
distortion °4)					732.1	5	2	260,864	5.b = 1.b
Alt.6 Simple node	360.0	8	5	264,174	334.6	6	3	239,466	6.a
distortion °2)					421.7	5	2	239,066	6.b = 2.b
Alt.6 Smart node	360.0	8	5	264,174	334.6	6	3	239,466	6.c = 6.a
distortion °2)					419.0	5	2	236,948	6.d
distortion °4)					398.7	5	3	235,100	6.e
Alt.7 Simple & Smart node	360.0	8	5	264,520	346.3	7	3	250,503	7.a
distortion °2)					398.0	6	3	253,046	7.b
distortion °3)					513.0	5	1	245,630	7.c
Alt.8 Simple node	360.0	8	5	265,509	392.8	5	2	228,602	8.a = 4.b
Alt.8 Smart node					384.7	5	2	226,721	8.b

°1) sequence: initial network / push up / pull down / restore

°2) sequence: optimise / pull down / restore

°3) sequence: optimise / pull down / restore / pull down / restore

°4) sequence: optimise / push up / pull down / restore

°5) sequence: initial network / push up / pull down to 5 / restore

°6) sequence: initial network / push up / pull down to 6 / restore / pull down to 5 / restore

°7) network identical with the network reported by Rezaei

References:

[1] Shenoy, U. V., 1995, Heat Exchanger Network Synthesis: Process Optimization by Energy and Resource Analysis (Gulf Publishing Co., Houston, TX, USA) .

[2] Rezae, E. Shafiei, S., An NLP Approach for Evolution of Heat Exchanger Networks Designed by Pinch Technology, Iranian Journal of Chemical Engineering Vol. 5, No. 1 (Winter), 2008, IAChE.

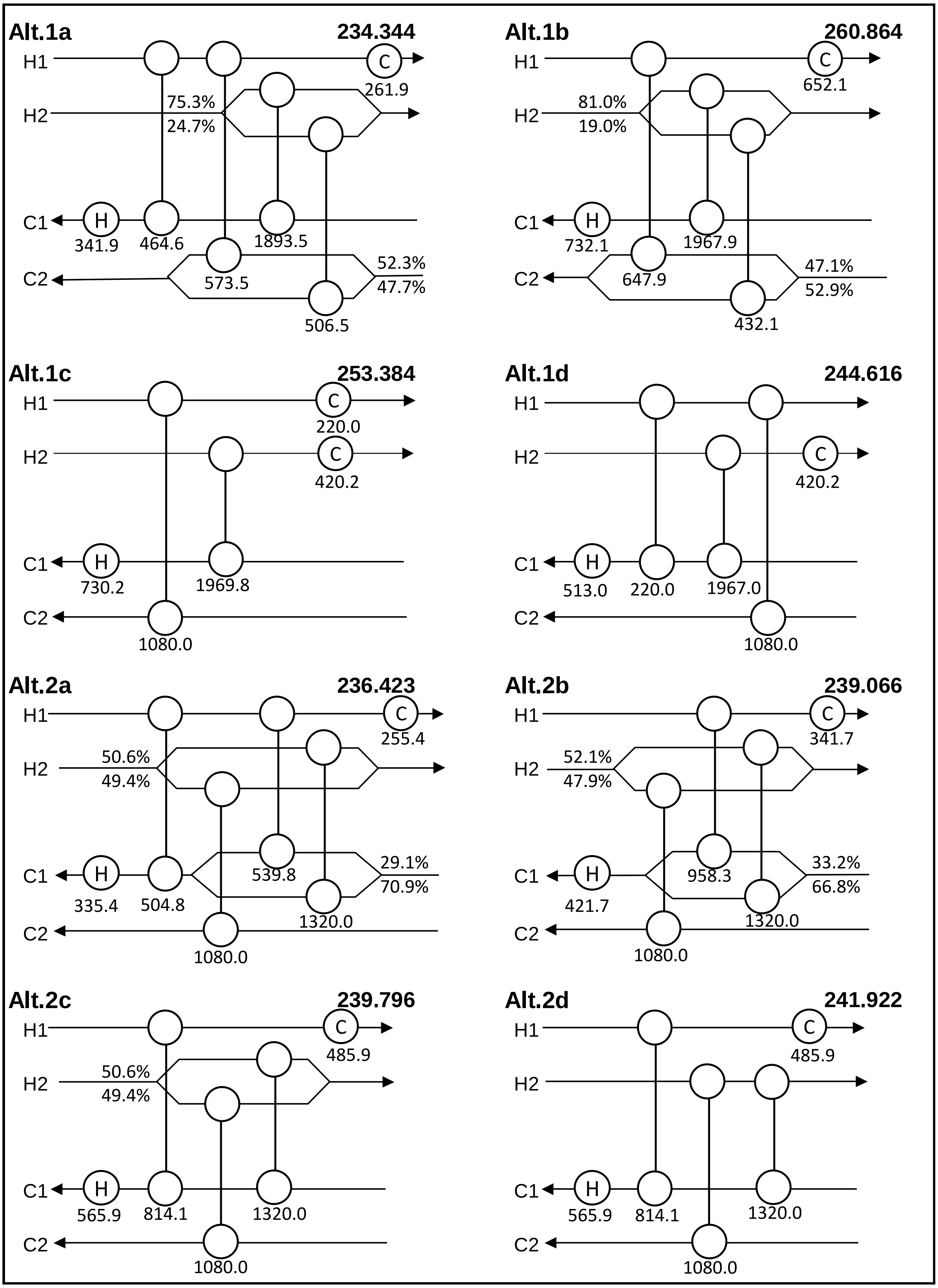

Figure 9: Networks of the various solutions.

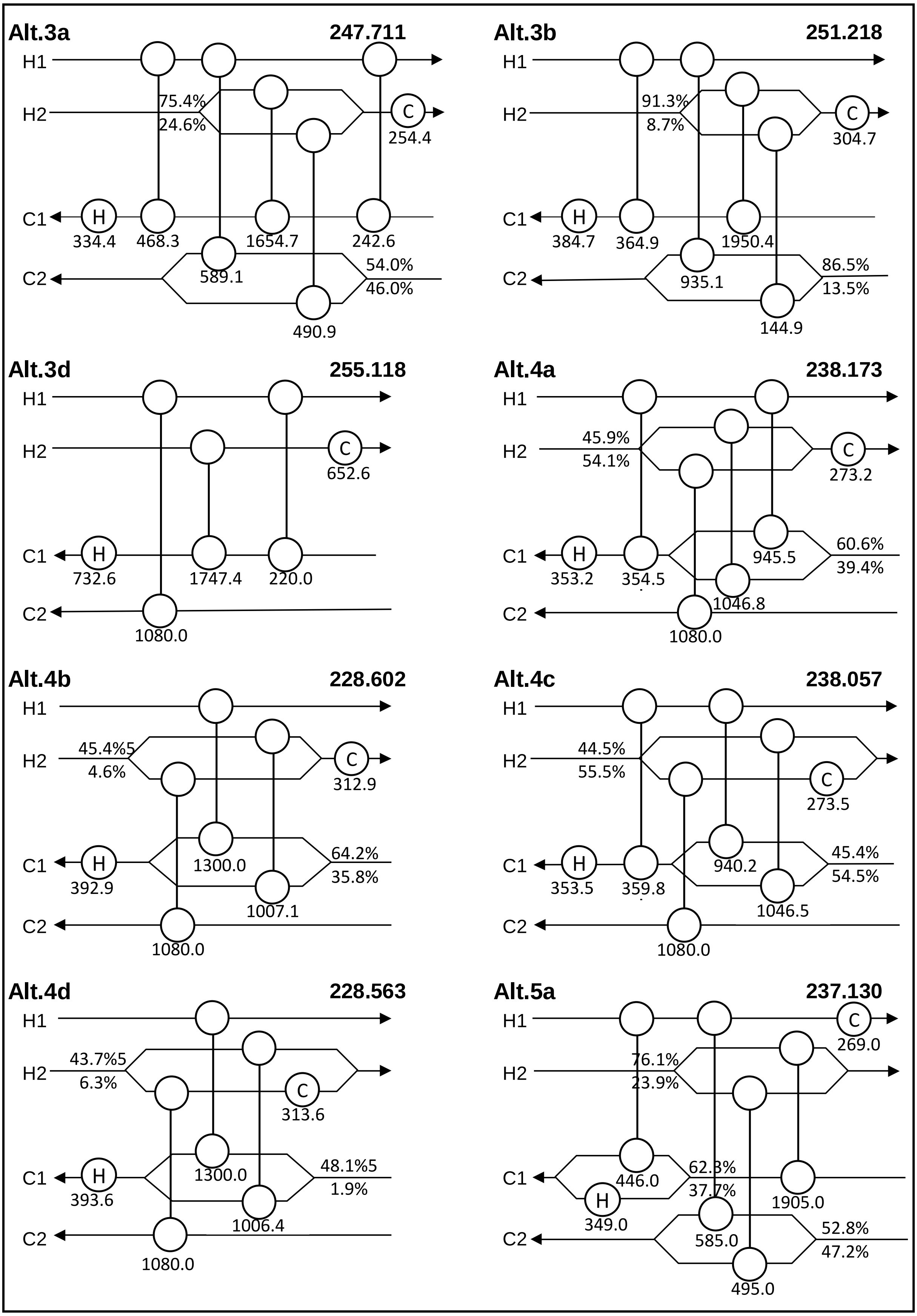

Figure 9: Networks of the various solutions (continued).

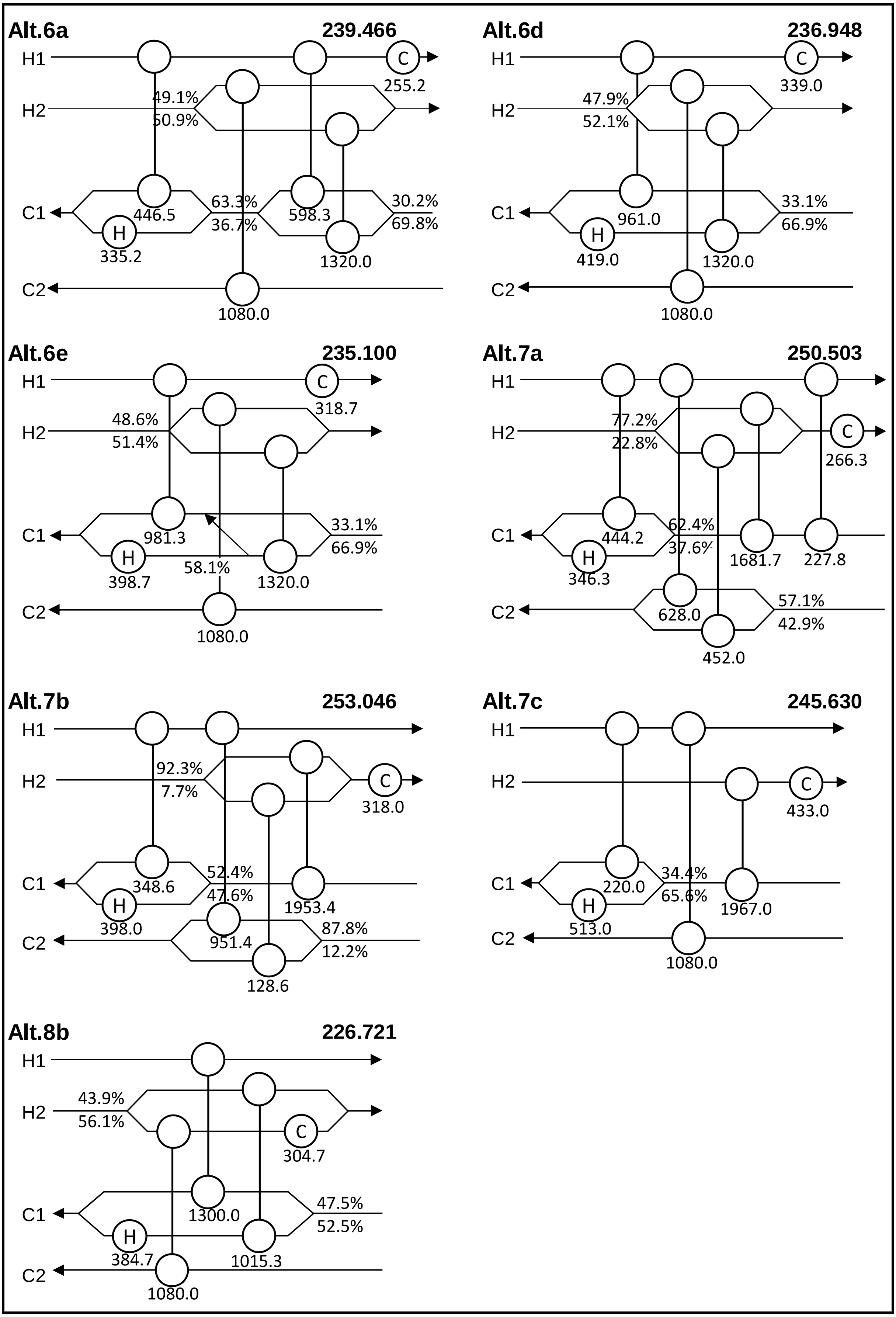

Figure 9: Networks of the various solutions (continued).