Pinch Analysis with crisscross optimization prior to design

Example Case 19 ï Data set from Ahmad ï Small scale problem

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Keywords: pinch analysis, heat exchanger network synthesis, crisscross optimization

Example case 19 has been treated many times and is interesting for several reasons: the temperature level of the hot utility is not the highest level in the system and has a low heat transfer coefficient, the heat transfer coefficients of the various process streams are not the same and the stream data set has been explored with small heat loads, with mid-size heat loads and with large heat loads (the latter, however, with heat transfer coefficients that are different from the other cases). The mid-size case was treated in Example Case 13.

This example problem is also interesting because it was defined as one of the most difficult practical problems for targeting purposes (Jegede and Polley, 1992).

The small scale problem differs from the mid-size problem by the heat capacity flow rates that are a factor of 10 smaller and by different HEX cost parameters. The data set is given in Table 19.1 with shift values optimized with the crisscross procedure for minimum surface area. The heating load has been chosen on the basis of the trade-off, illustrated in Fig.19.1, ñCrisscross ï 1 systemò and would correspond with an overall DTMin of 35.3°C in classic pinch analysis. This value is remarkably close to the value in the medium size problem, indicating the same degree of integration with a difference of only 1%, notwithstanding different HEX cost parameters.

Table 19.1

Tsupply	Ttarget	Heat	Shift	U	Description
°C	°C	kW	K	kW/m²,K	-
159	77	187.37	2.0	0.10	H1
267	80	38.15	13.0	0.04	H2
343	90	136.11	-6.0	0.50	H3
26	127	94.23	58.0	0.01	C1
118	265	288.27		0.50	C2
300	300	159.00	41.0	0.05	Heating
20	60	138.13		0.20	Cooling

Hot utility = 110 EUR/kW,year Cold utility = 10 EUR/kW,year

HEX cost formula = 872.51 + 172.21*Area $^{0.83}$

There is a large difference in the results of the various trade-off curves. In the typical ñpinch analysisò approach the grid is segregated in 2 systems, one above the pinch and one below the pinch; this will increase the total number of units and the target cost. Experience has shown that economic networks are often feasible with a lower number of units and, therefore, another trade-off is done assuming the minimum number of units in a single system. The target with crisscross and 1 system is 15% lower than the target with classic pinch analysis with 2 systems.

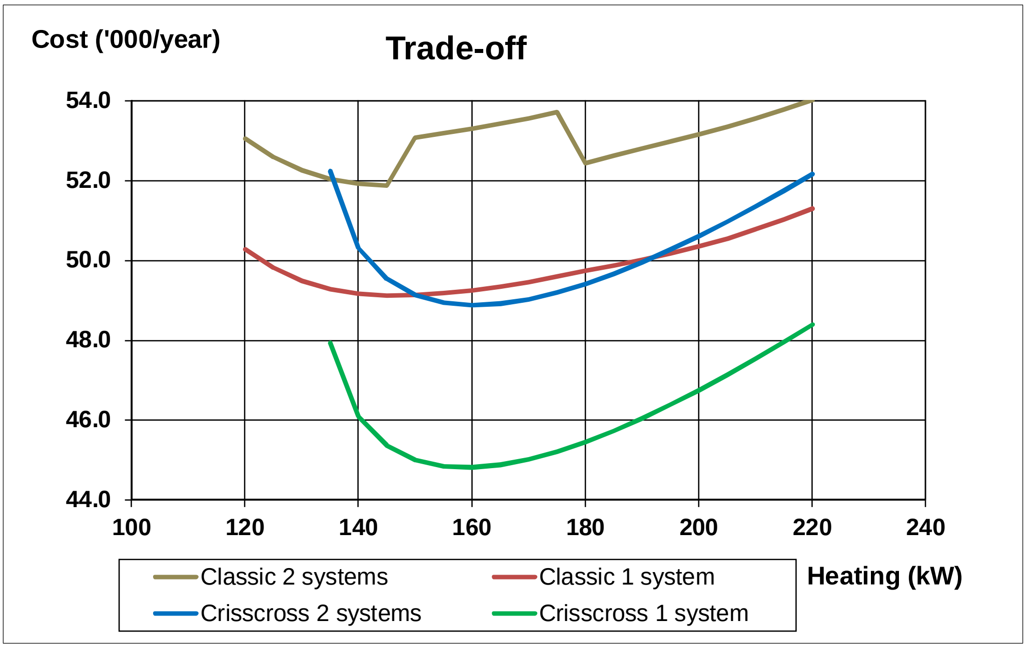

Fig.19.1 ï Trade-off small scale problem

Shift values can also be optimized for other heating loads as illustrated in Fig.19.2. If trade-off is applied with crisscross optimized for a heating load below the optimum, say, for 140 kW, then the trade-off curve will show a minimum at a higher heating load. If trade-off is applied with crisscross optimized for a heating load above the optimum, say, for 180 kW, then the trade-off curve will show a minimum at a lower heating load. Convergence is obtained when the trade-off curve confirms the heating load that has been chosen.

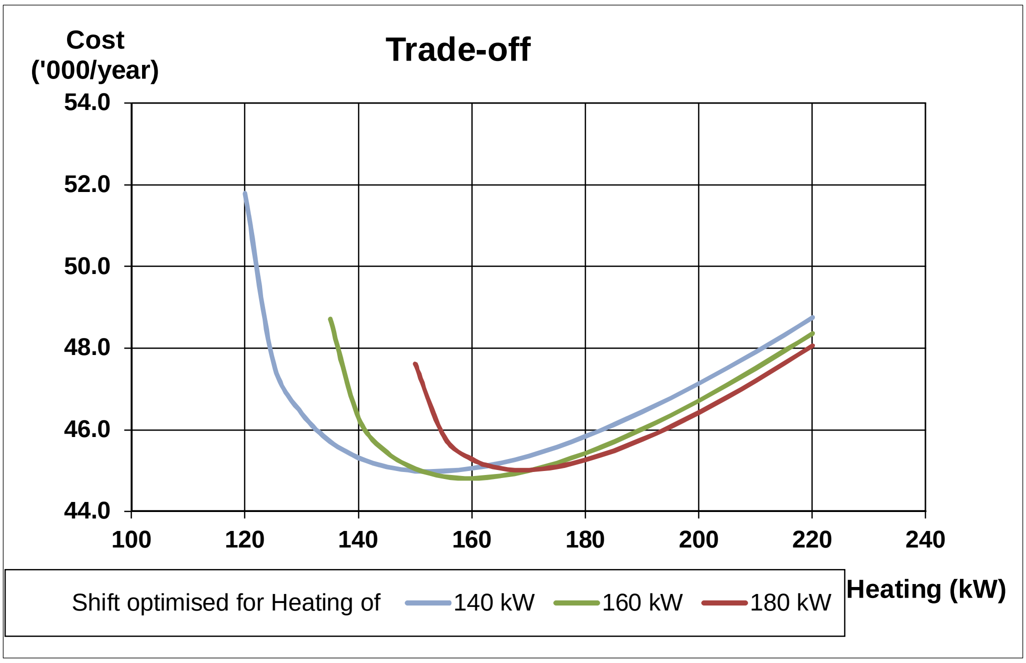

Fig.19.2 ï Trade-off optimization

Whilst there is agreement about the optimum heating load using classic pinch analysis (146.7 kW) other authors take a different approach when using differentiated shift contributions. In the approach based on the ñdiverse pinchò concept shift values are calculated according to the formula

$$\Delta T_i = \kappa \, . \, h^{-z}$$

Two studies applying the diverse pinch concept have been analysed and compared with crisscross optimization. The first study was carried out by Zhu et al. (1995, 1997), the second by Serna-González et al. (2004, 2007). The data of Serna-González were derived from those for the midsize problem that has identical stream characteristics which, consequently, should generate congruent targets.

Zhu allocated differentiated DTMin contributions (shifts) to the process streams only. The area was calculated with the ñdiverse Bath formulaò proposed by Rev& Fonio (1991). The optimum heating load was found to be 161.32 kW.

Serna-González allocated differentiated shift values to process streams and utilities. The area was calculated for a spaghetti network in each vertical integration band of the shifted composite curves diagram. This formula, put forward by Ahmad (1985), is sometimes called the ñpseudo-Bathò formula although it lacks the main characteristic of the Bath formula which is that the area contribution of any hot (cold) stream is invariant with regard to the area contribution of any cold (hot) stream in any vertical integration band. The formula used is the correct calculation of the area of a spaghetti network in which any hot (cold) stream is split according to the weight of the opposite cold (hot) streams.

The results of the comparison are shown in Table 19.2.

As can be seen in Table 19.2 there are significant differences between the calculated optimum heating loads and corresponding shift values, As a consequence, also the grids are different and so are the potential initial designs.

Table 19.2

Shift values Heating 161.32 kW		
	Diverse pinch Zhu	Crisscross Declercq
Stream	K	K
H1	5.817	8
H2	17.466	17
H3	0.843	0
C1	92.186	60
C2	0.843	0
Heating	0.0	47
Cooling	0.0	0

Shift values Heating 145.67 kW		
	Diverse pinch Serna	Crisscross Declercq
Stream	K	K
H1	11.051	7
H2	20.987	17
H3	3.582	0
C1	55.384	50
C2	3.582	0
Heating	18.0	47
Cooling	6.8	0

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The grid resulting from the pinch analysis has 10 vertical integration bands and, after optimization of the spaghetti network, would lead to a network with 24 units. The number of bands can be reduced from 10 to 6 without changing the nature of the problem as shown in Table 19.3 for a heating load of 149 kW. For the comparison, the bands have been reduced to 4, corresponding with the 4 blocks reported by Zhu; the number of units is thereby reduced to 12. The results are shown in Table 19.4.

Table 19.3

Analysis Bands 10 Area (Spaghetti) 222.07

Design Bands 10 Area (LP) 215.51 # HEX 24

Stream	mcp	Bands																				
	kW/K		1		2		3		4		5		6		7		8		9		10	
Heating	15900.00			300.01		300.00		300.00														
H1	2.29											159.00		136.31		125.83		98.00		77.00		
H2	0.20									267.00		170.00		147.31		136.83		109.00		88.00		80.00
H3	0.54	343.00		253.01		253.00		253.00		248.00		151.00		128.31		117.83		90.00				
C1	0.93					127.00		109.54		108.61		83.74		60.00		26.00						
C2	1.96	265.00		240.31		185.00		167.54		166.61		141.74		118.00								
Cooling	3.45															60.00		35.61		20.47		20.00

Design Bands 6 Area (LP) 215.62 # HEX 17

Stream	mcp	Bands												
	kW/K		1		2		3		4		5		6	
Heating	15900.00			300.01		300.00								
H1	2.29							159.00		136.31		125.83		77.00
H2	0.20					267.00		170.00		147.31		136.83		80.00
H3	0.54	343.00		253.01		248.00		151.00		128.31		117.83		90.00
C1	0.93			127.00		108.61		83.74		60.00		26.00		
C2	1.96	265.00		240.31		166.61		141.74		118.00				
Cooling	3.45											60.00		20.00

Table 19.4

	Heating 161.32 kW			Heating 145.67 kW		
	# bands	# HEX	Area	# bands	# HEX	Area
	-	-	m²	-	-	m²
Diverse pinch		Zhu			Serna	
Spaghetti network	10		278.54	10		248.64
LP	10	24	272.57	10	24	241.18
Initial design	4	12	281.37	NA	NA	NA

Crisscross for same Heating		Declercq			Declercq	
Spaghetti network	10		218.61	10		245.96
LP	10	24	212.00	10	24	238.55
Initial design with same block structure						
	4	12	235.21	4	12	242.01

The spaghetti network can be optimized using LP, targeting for minimum area; simultaneously a minimum number of units is achieved. There are many alternatives for reducing the number of integration bands below 6; the results of most obvious possibilities are shown in Table 19.6; the underlying grids are shown in Tables 19.7 A & B.

Initial designs can be simplified automatically by simple means such as incremental evolution, or manually; split ratios can be optimized. The initial design following Grid# 10 is shown in Fig. 19.3 and automatically developed by incremental evolution into Fig. 19.4. Merging the double split on cold stream C2 into one and split optimization generates the lowest cost network of Fig. 19.5; the split on hot stream H1 can be eliminated with a negligible penalty (Fig. 19.6) and the number of units can be reduced to 6 (Fig. 19.7). Other low cost networks are shown in Fig. 19.8 through Fig. 19.10.

The overview in Fig. 19.11 shows a large number of networks that can be developed with a cost below the targeted cost from classic pinch analysis. The best results are summarized in Table 19.5.

Table 19.5

Heating kW	Area m²	Total Cost '000	# HEX	Splits
145.30	255.03	46.0672	7	3
141.90	262.04	46.0675	7	2
156.50	251.96	46.219	6	2
144.30	280.69	46.275	7	1
170.90	234.84	46.315	6	2
141.10	255.02	46.496	8	1
(*) 169.2	242.28	46.552	6	1

(*) Network developed by Zhu

The example case described illustrates the benefits of the crisscross procedure in the analysis stage, generating an optimum data set for synthesis of an initial network. The applied procedures lead to better networks than those developed by other authors using the diverse pinch method.

Table 19.6 ï Results initial designs with alternative block structures

Grid	# bands	# HEX	Area
	-	-	m^2
1	6	17	216.04
2	5	16	220.89
3	5	15	225.04
4	4	14	219.46
5	4	13	220.88
6	4	12	245.14
7	4	14	230.29
8	3	12	228.86
9	3	11	230.28
10	3	10	254.54

Table 19.7 A ï Grids for initial designs

Grid # 2 16 Units Area 220.89 m^2

Band		1		2		3		4		5	
Heating	300.01		300.00								
H1					159.00		136.31		125.83		77.00
H2			267.00		170.00		147.31		136.83		80.00
H3	343.00		248.00		151.00		128.31		117.83		90.00
C1	127.00		108.61		83.74		60.00		26.00		
C2	265.00		166.61		141.74		118.00				
Cooling									60.00		20.00

Grid # 3 15 Units Area 225.04 m^2

Band		1		2		3		4		5	
Heating			300.01		300.00						
H1					159.00		136.31		125.83		77.00
H2			267.00		170.00		147.31		136.83		80.00
H3	343.00		253.01		151.00		128.31		117.83		90.00
C1			127.00		83.74		60.00		26.00		
C2	265.00		240.31		141.74		118.00				
Cooling									60.00		20.00

Grid # 4 14 Units Area 219.46 m^2

Band		1		2		3		4	
Heating	300.01		300.00						
H1			159.00		136.31		125.83		77.00
H2	267.00		170.00		147.31		136.83		80.00
H3	343.00		151.00		128.31		117.83		90.00
C1	127.00		83.74		60.00		26.00		
C2	265.00		141.74		118.00				
Cooling							60.00		20.00

Grid # 5 13 Units Area 220.88 m^2

Band		1		2		3		4	
Heating	300.01		300.00						
H1			159.00		136.31		125.83		77.00
H2			267.00		147.31		136.83		80.00
H3	343.00		151.00		128.31		117.83		90.00
C1	127.00		104.95		60.00		26.00		
C2	265.00		141.74		118.00				
Cooling							60.00		20.00

Table 19.7 B ï Grids for initial designs

Grid # 6 12 Units Area 245.14 m^2

Band		1	2	3	4
Heating	300.01	300.00			
H1		159.00	136.31	125.83	77.00
H2		267.00	147.31	136.83	80.00
H3	343.00	151.00	128.31	117.83	90.00
C1		127.00	60.00	26.00	
C2	265.00	131.24	118.00		
Cooling				60.00	20.00

Grid # 7 14 Units Area 230.29 m^2

Band		1	2	3	4
Heating	300.01	300.00			
H1			159.00	136.31	77.00
H2		267.00	170.00	147.31	80.00
H3	343.00	248.00	151.00	128.31	90.00
C1	127.00	108.61	83.74	60.00	26.00
C2	265.00	166.61	141.74	118.00	
Cooling				60.00	20.00

Grid # 8 12 Units Area 228.86 m^2

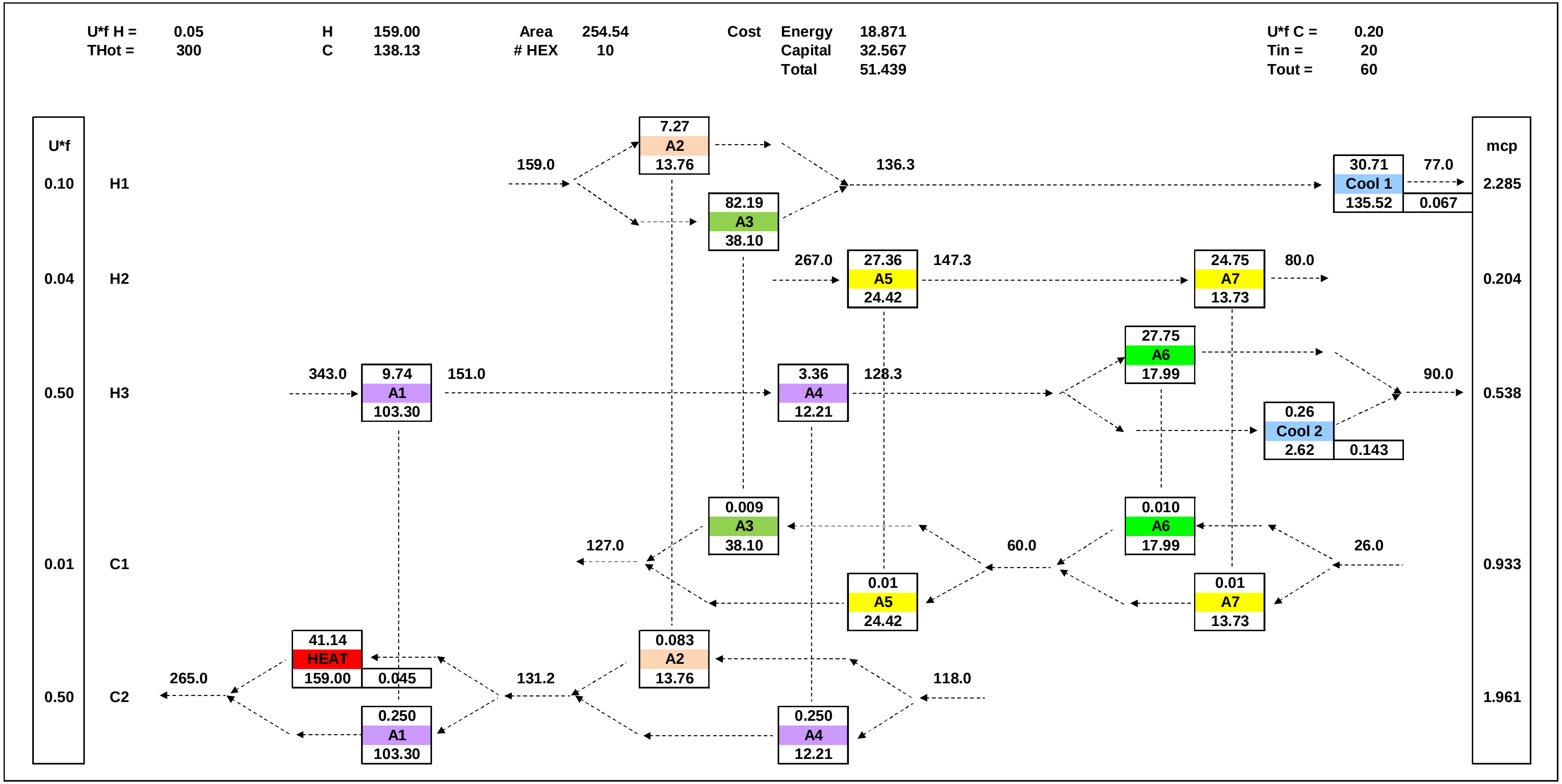
Band		1	2	3
Heating	300.01	300.00		
H1		159.00	136.31	77.00
H2	267.00	170.00	147.31	80.00
H3	343.00	151.00	128.31	90.00
C1	127.00	83.74	60.00	26.00
C2	265.00	141.74	118.00	
Cooling			60.00	20.00

Grid # 9 11 Units Area 230.28 m^2

Band		1	2	3
Heating	300.01	300.00		
H1		159.00	136.31	77.00
H2		267.00	147.31	80.00
H3	343.00	151.00	128.31	90.00
C1	127.00	104.95	60.00	26.00
C2	265.00	141.74	118.00	
Cooling			60.00	20.00

Grid # 10 10 Units Area 254.54 m^2

Band		1	2	3
Heating	300.01	300.00		
H1		159.00	136.31	77.00
H2		267.00	147.31	80.00
H3	343.00	151.00	128.31	90.00
C1		127.00	60.00	26.00
C2	265.00	131.24	118.00	
Cooling			60.00	20.00


U*f H = 0.05
THot = 300
H 159.00
C 138.13
Area 254.54
HEX 10
Cost
Energy 18.871
Capital 32.567
Total 51.439
U*f C = 0.20
Tin = 20
Tout = 60
U*f
0.10
0.04
0.50
0.01
0.50
H1
H2
H3
C1
C2
mcp
2.285
0.204
0.538
0.933
1.961
159.0
7.27
A2
13.76
136.3
82.19
A3
38.10
30.71
Cool 1
135.52
77.0
0.067
267.0
27.36
A5
24.42
147.3
24.75
A7
13.73
80.0
27.75
A6
17.99
343.0
9.74
A1
103.30
151.0
3.36
A4
12.21
128.3
90.0
0.26
Cool 2
2.62
0.143
0.009
A3
38.10
127.0
60.0
0.010
A6
17.99
26.0
0.01
A5
24.42
0.01
A7
13.73
41.14
HEAT
159.00
0.045
265.0
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A2
13.76
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103.30
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A4
12.21

Fig. 19.3

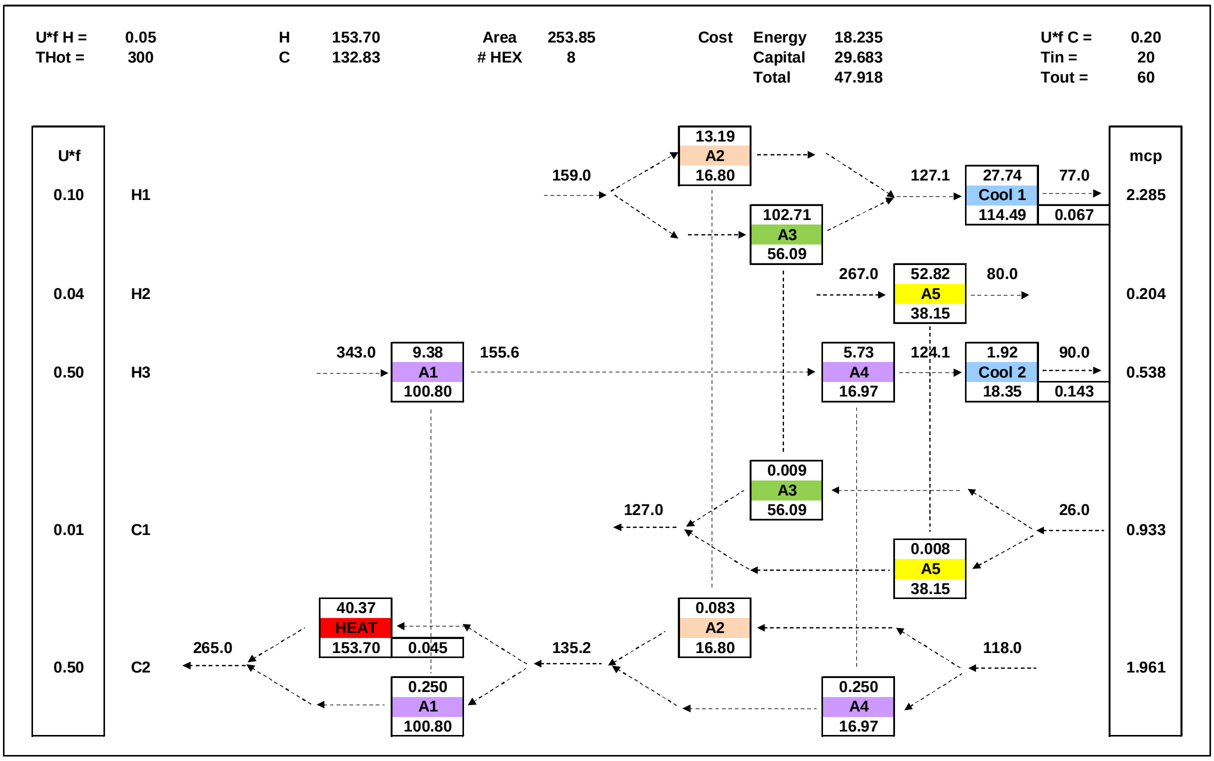

Fig. 19.4

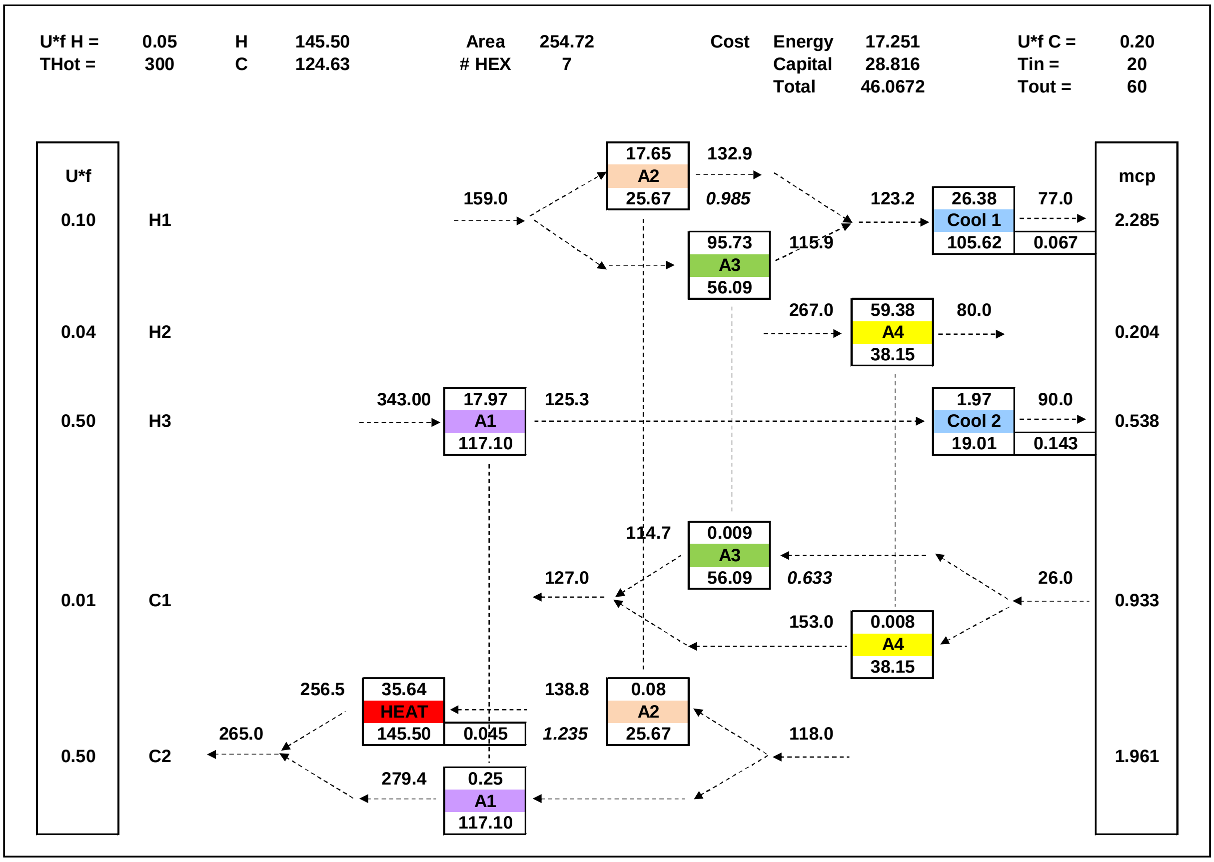

Fig. 19.5

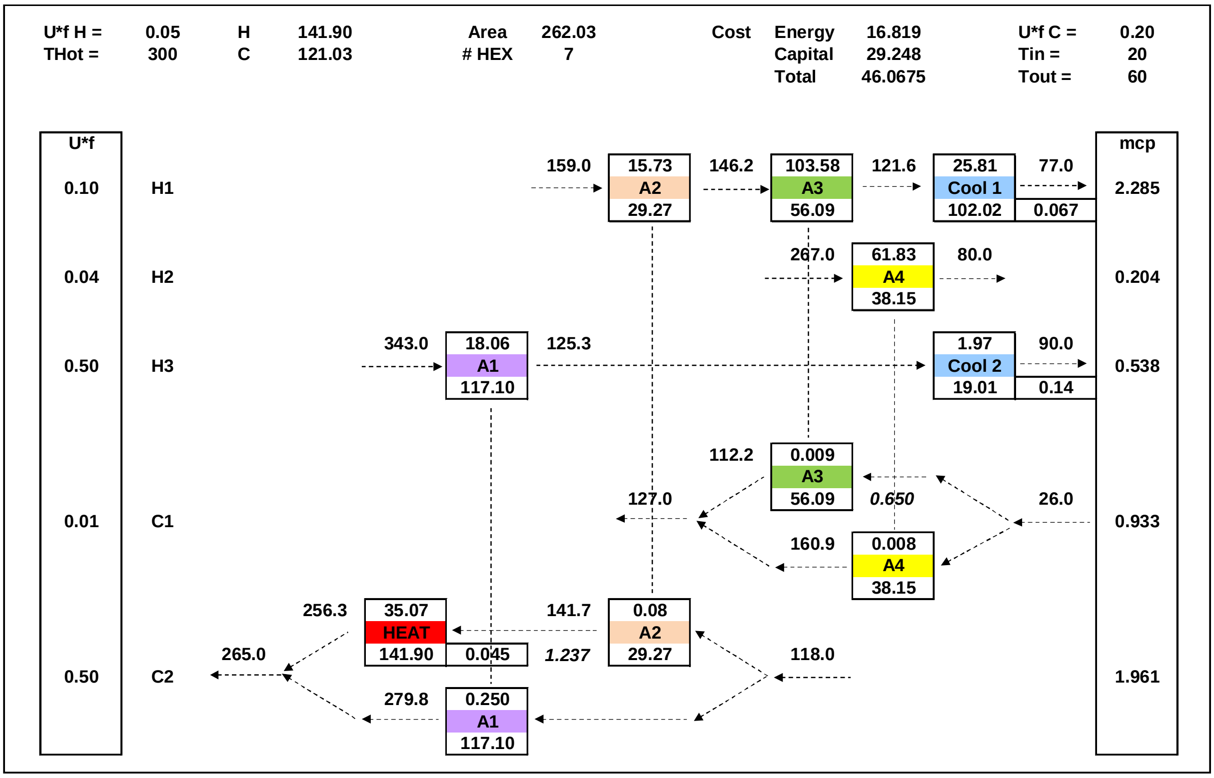

Fig. 19.6

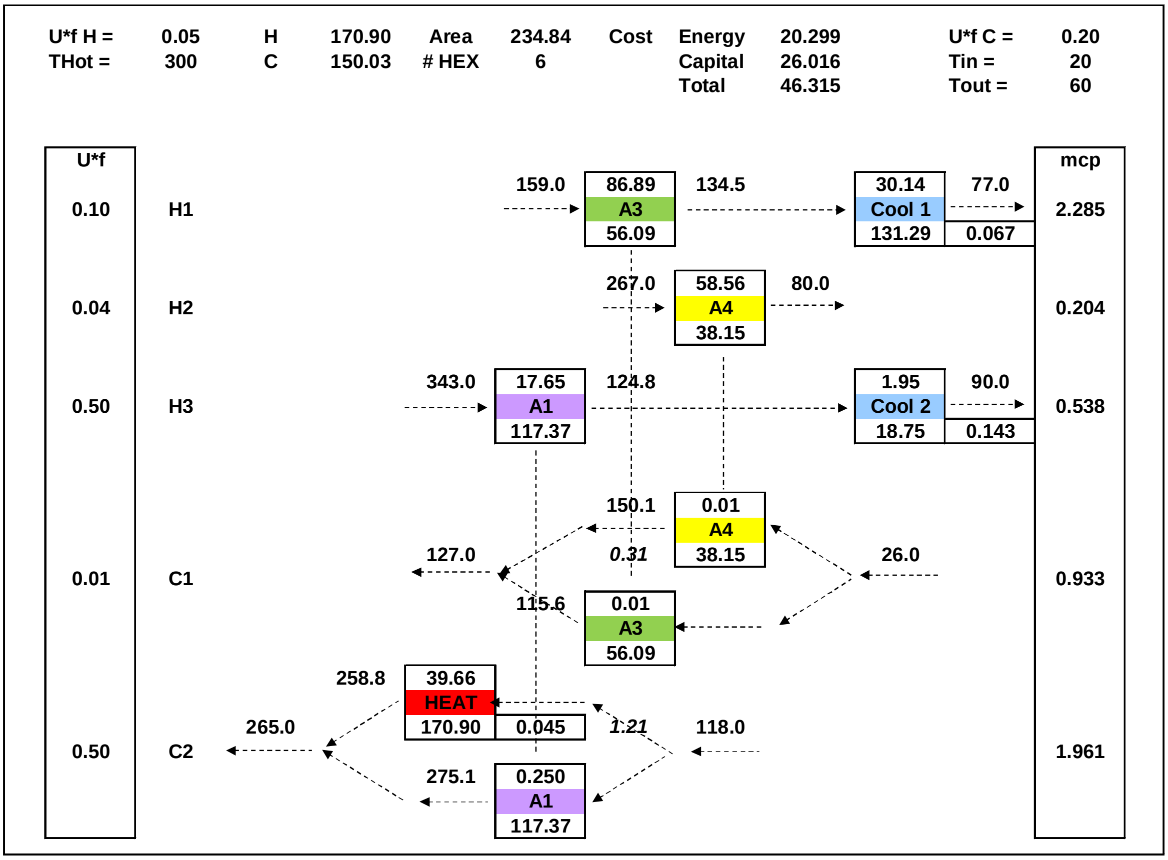

Fig. 19.7

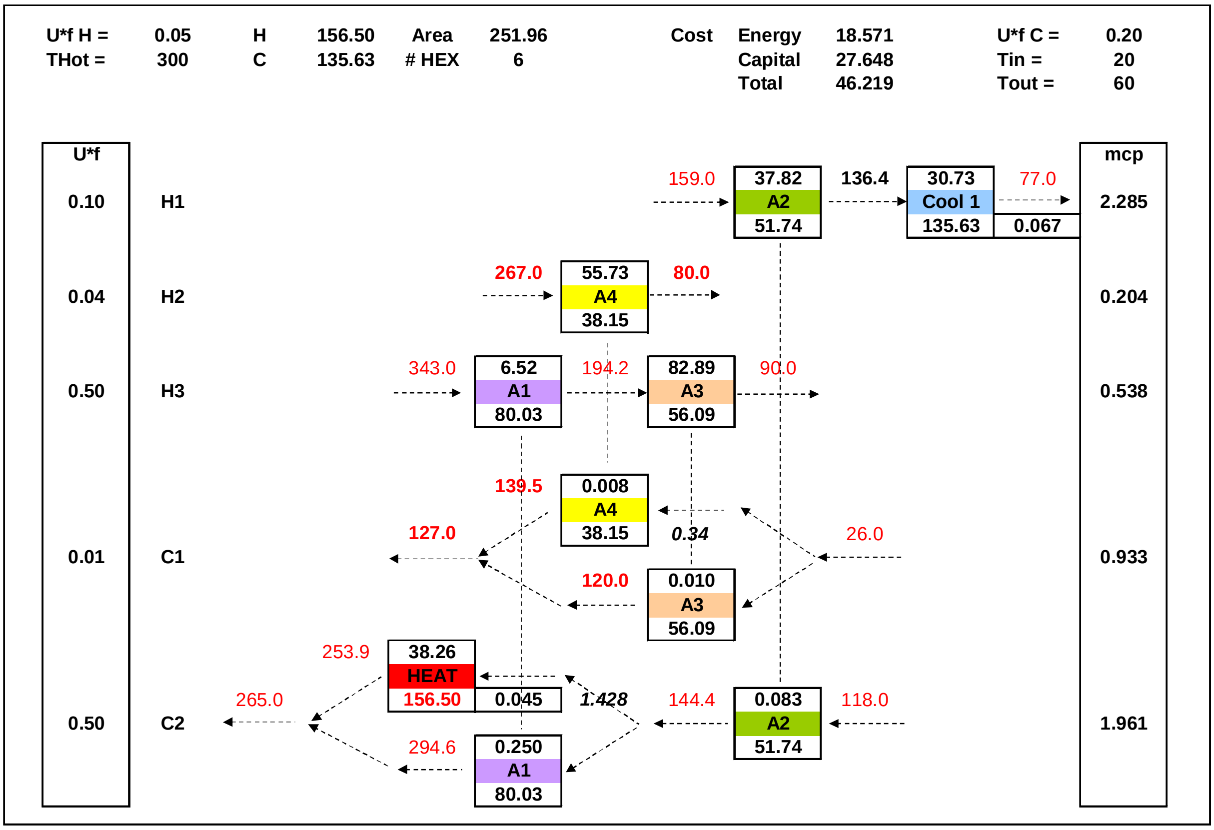

Fig. 19.8

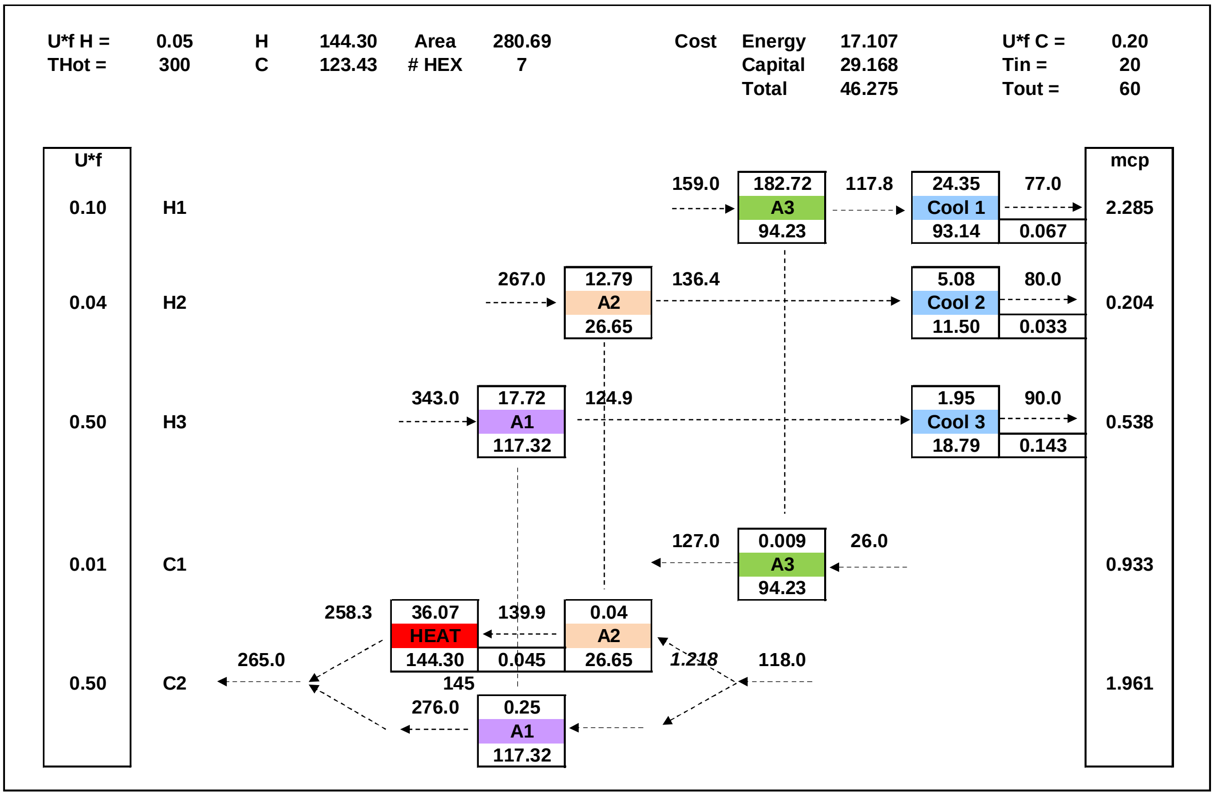

Fig. 19.9

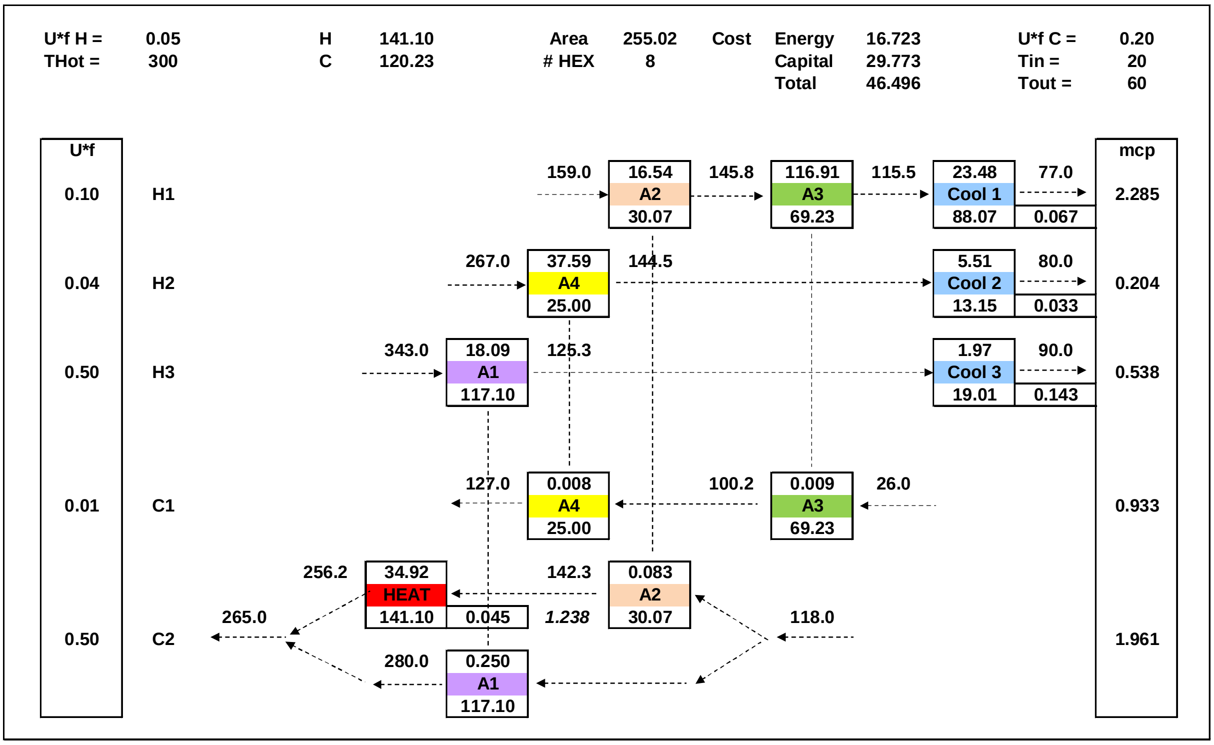

Fig. 19.10

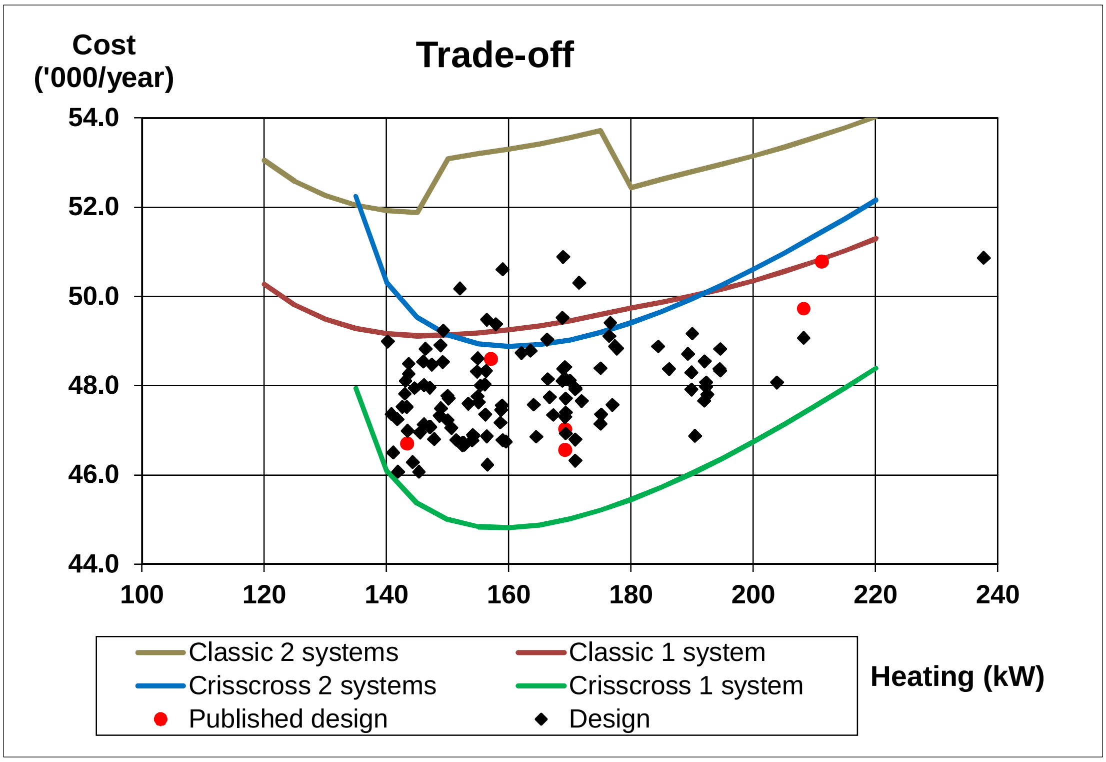

Fig. 19.11