Case 27 – Pinch analysis in case of multiple utilities.

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Introduction

Pinch analysis has been widely used as a tool to reduce energy consumption and increase efficiency in industrial processes. Numerous studies have been published on synthesis of the heat exchanger networks to achieve economically optimal solutions, using most complicated procedures from Mixed Integer Non-Linear Programming to Tabu Search, Genetic Algorithms, Simulated Annealing and many more. Little attention has been paid, however, to improving the analysis procedure itself. The following examples will show how further developed pinch analysis can facilitate the targeting process and generate a more reliable grid as starting point for design of a network, specifically in case of multiple utilities.

Example 1

The first example has 2 hot streams, 1 cold stream, 3 hot utilities and 1 cold utility. It was used by Shenoy et al. [1], Isafiade and Fraser [2], Ponce-Ortega et al. [3], Huang & Karimi [4], Na et al. [5] and Yang et al. [6] to demonstrate procedures in case of multiple utilities. Although it was discussed extensively by this author in 2016 [7], the very specifics of the approach regarding multiple utilities will be repeated here.

The data set is shown in Table 27.1, cost figures in Table 27.2.

Table 27.1

Tsupply	Ttarget	Heat	Shift	U*f	Descrip	mcp
°C	°C	kW	K	kW/m²,K	-	kW/K
105	25	800	10	0.50	H1	10.00
185	35	750	10	0.50	H2	5.00
25	185	1200	10	0.50	C1	7.50
210	209		10	5.00	HP Steam	
160	159		10	5.00	MP Steam	
130	129		10	5.00	LP Steam	
5	6			2.60	Cooling	

Table 27.2

Utility costs		**Capital cost**		
	$/kW,year	HEX area	800 $/m²	
HP Steam	160.0	annuiity	0.298	
MP Steam	110.0	Cost/year	238.4 $/m²,year	
LP Steam	50.0			
Cooling	10.0			

A first assessment of the steam requirements for a few values of a global DTMin leads to Table 27.3. It is obvious that a global DTMin of 20 K will be a good starting point; the best result is obtained with a DTMin of 19.5 K.

Table 27.3

Cost in k$/y	**Trade-off with Global DTMin**			**Best**
DTMin (K)	15.0	20.0	25.0	19.5
HP steam	175.0	212.5	250.0	208.75
MP steam	75.0	75.0	75.0	75.00
LP steam	62.5	62.5	62.5	62.50
Cooling	662.5	700.0	737.5	696.25
Cost	98.240	96.919	98.200	96.906

Table 27.3 shows that only the HP Steam target is changing with changing DTMin. Obviously, the global DTMin parameter is not necessarily suited for a reliable trade-off between energy and capital cost in case of multiple utilities. So, trade-off will be done with the heating loads as parameter, one by one, in a sequence from low to high total heating. For each utility, the optimum load will be defined by the minimum cost. This process will be repeated until sufficient convergence is reached. The result of 11 runs with steam loads as parameters is shown in Table 27.4. Convergence is reached on a cost figure of 96 365 $/year.

Table 27.4

Cost in k$/y	**Trade-off steps - heating loads as parameters**					
	Start	I	II	III	IV	V
HP steam	212.5	210	208	206.5	205.5	205.9
MP steam	75	57.5	52.0	50.0	50	50.5
LP steam	62.5	87.5	106.0	115.0	118.8	119.5
Cooling	700.0	705.0	716.0	721.5	724.3	725.9
Cost	96.919	96.547	96.401	96.371	96.366	96.366

Cost in k$/y	**Trade-off steps - heating loads as parameters**					
	VI	VII	VIII	IX	X	XI
HP steam	205.15	204.6	204.2	203.95	203.75	203.6
MP steam	50.40	50.8	51.3	51.7	52.1	52.3
LP steam	118.75	119.65	119.8	119.7	119.6	119.4
Cooling	724.30	725.1	725.30	725.35	725.35	725.30
Cost	96.366	96.365	96.365	96.365	96.365	96.365

Since heat transfer coefficients of process streams and utilities are quite different, trade-off will be repeated with crisscross optimization. The result is shown in Table 27.5. Convergence on the cost figure is reached with a value of 96 044 $/year after 11 runs. Expectedly, this is also the lowest value that is achievable with any procedure in the targeting stage, the ultimate values being shown in the column marked with ∞ in Table 27.5.

Shift values for MP and LP steam were set at -6 K; these could be further refined to -5.99 K for MP steam and -5.88 K for LP steam, with only negligible improvements, however, and no impact on final networks.

Table 27.5

Cost in k$/y	**Trade-off steps - heating loads as parameters**						
	Shift	Start	I	II	III	IV	V
HP steam	0	212.5	210	207.5	205	203.5	202.5
MP steam	-6	75	57.5	50.0	49.0	49.5	51.0
LP steam	-6	62.5	87.5	110.0	119.0	123.5	124.0
Cooling		700.0	705.0	717.5	723.0	726.5	727.5
Cost with crisscross		96.345	96.287	96.093	96.059	96.052	96.048

Cost in k$/y	**Trade-off steps - heating loads as parameters**							
	Shift	VI	VII	VIII	IX	X	XI	∞
HP steam	0	201.0	200.6	200.25	199.95	199.80	199.70	199.50
MP steam	-6	52.0	53.2	54.05	54.65	55.00	55.25	55.80
LP steam	-6	124.0	124.3	123.45	122.95	122.65	122.45	122.00
Cooling		727.0	728.1	727.75	727.55	727.45	727.40	727.30
Cost with crisscross		96.047	96.046	96.045	96.044	96.044	96.044	96.044

Composite curves for the optimum target values are shown in Figure 27.1, the Grand Composite for a global DTMin of 17.71 K with shift corrections of -6 K for MP steam and LP steam is shown in Figure 27.2.

For this example, the cost targets obtained by the different methods do not differ very much in contrast to the values of the steam load targets. As shown in Table 27.6, in the classic approach with DTMin as parameter, the errors for MP and LP steam loads are unacceptable. The results with trade-off using steam loads as parameters are much closer to the achievable optimum; the results with trade-off using steam loads combined with crisscross optimization are right on target for the cost and deviations in steam loads are less than 1%.

Table 27.6

		Parameter	DTMin		Steam loads		Steam loads	
		Trade-off target	**Classic**	**deviation**	**Classic**	**deviation**	**Crisscross**	**deviation**
HP steam	kW	199.5	208.8	4.7%	203.6	2.1%	199.70	0.10%
MP steam	kW	55.8	75.0	34.4%	52.3	-6.3%	55.25	-0.99%
LP steam	kW	122.0	62.5	-48.8%	119.4	-2.1%	122.45	0.37%
Cost	'000	96.044	96.906	0.9%	96.366	0.3%	96.044	0.0%

The grid diagrams for the classic approach and for the analysis with crisscross optimization are shown in Table 27.8. It can easily be seen that the HEN structures will be identical and in both cases the targets are fully achievable. The classic grid leads to a network with 12 units and a cost of 96.919 k$/y; the cost for the network using the crisscross grid is 96.046 k$/y. Evolution of the networks will result in the same network with 10 units, that also is the network with the lowest cost (96,041). This network can be simplified further by reducing the number of units at a marginally higher cost.

The results are summarized in Table 27.7 and compared with those of best published HENs (adjusted for correct heat exchanger DTLnM instead of approximations). The network with 7 units is identical with that of Ponce-Ortega et al. The best networks with and without splits are shown in Figures 27.3.

Table 27.7

	HP Steam	MP Steam	LP Steam	Total Steam	# HEX	# splits	Area	Cost
	kW	kW	kW	kW	-	-	m²	'000
Shenoy et al.	203.0	53.0	119.5	375.5	9	0	195.78	98.214
	240.0	0.0	135.5	375.5	7	0	193.87	98.649
Isafiade & Frazer °)	244.60	1.00	143.70	389.30	9	0	181.36	97.063
Ponce-Ortega et al.	238.7	0	151.3	390.0	7	0	184.09	97.043
Huang & Karimi	221.1	27.0	142.6	390.7	8	1	185.16	97.026
Na et al. °)	199.3	56.1	122.0	377.4	10	1	187.11	96.041
Yang et al.	199.26	56.10	121.96	377.32	10	1	187.15	96.041

°) reviewed

This work								
Targeting	199.7	55.3	122.45	377.4	7	-	187.16	96.044
Design	199.7	55.3	122.45	377.4	12	3	187.16	96.046
	199.2	56.0	122.1	377.3	10	1	187.21	96.041
	199.2	33.2	140.2	372.6	10	0	186.58	96.262
	199.3	55.9	135.2	390.4	9	0	186.04	96.552
	238.4	0	138.9	377.3	8	1	185.27	96.531
	238.4	0	145.1	383.5	8	0	184.64	96.752
	238.3	0	152.1	390.4	7	0	184.17	97.043

Figure 27.1

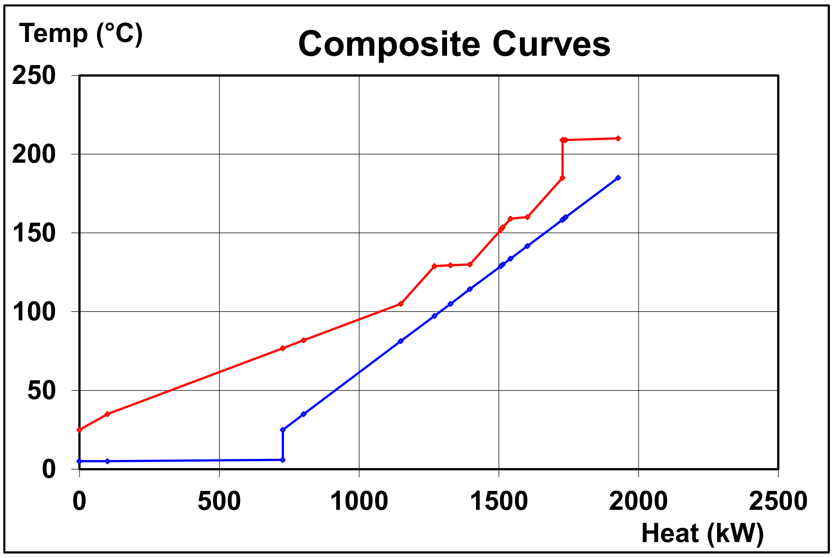


Figure 27.2

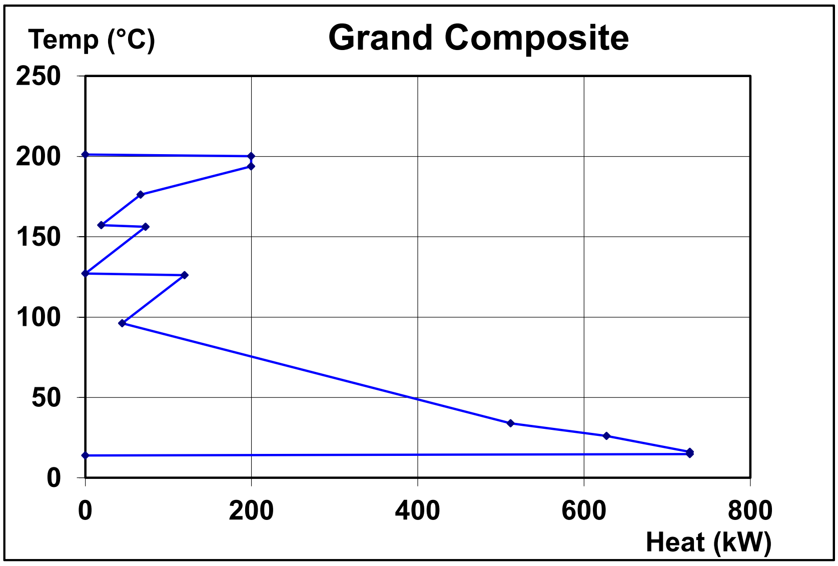


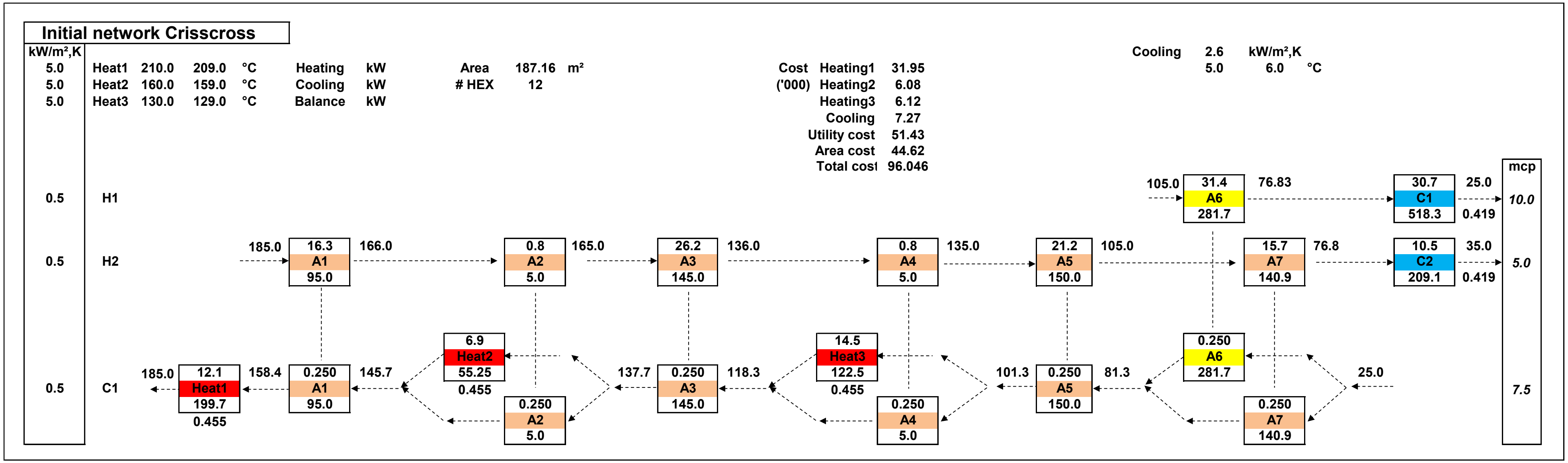
Table 27.8

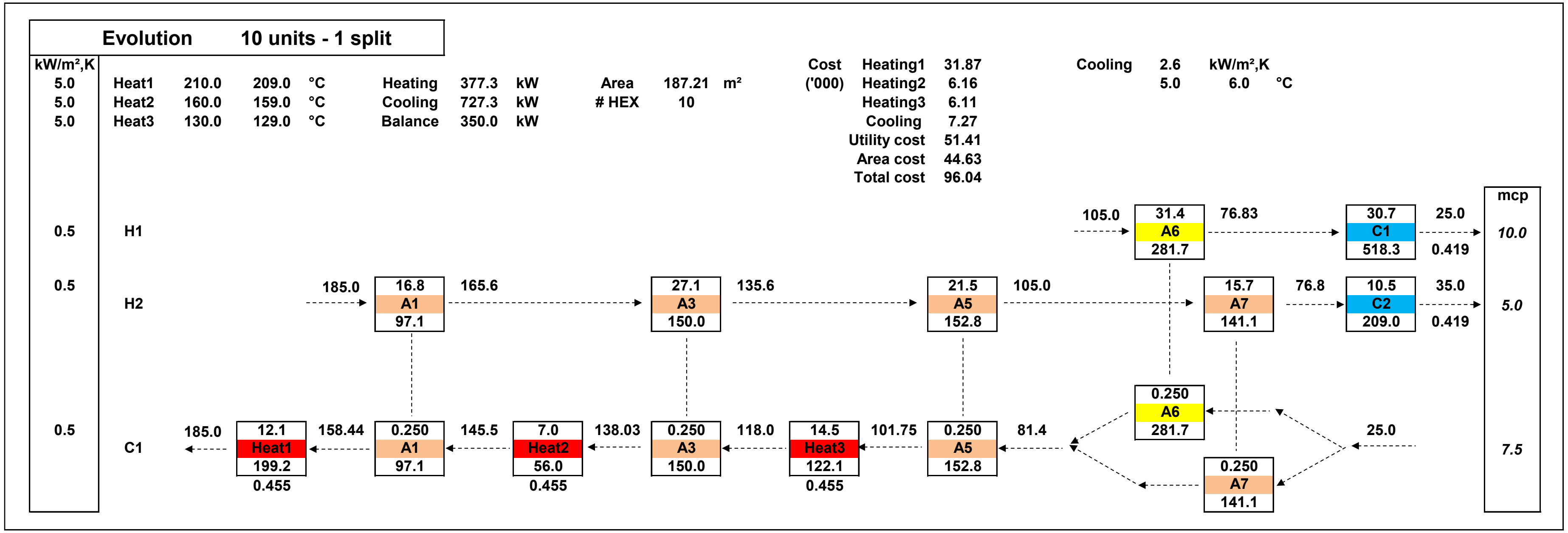
Description		1		2		3		4		5		6		7		8		9	
-	°C	kW	°C	kW	°C	kW	°C	kW	°C	kW	°C	kW	°C	kW	°C	kW	°C	kW	°C
HP Stean	210.0	**212.5**	209.0																
MP Stean					160.0	**75.0**	159.0												
LP Stean									130.0	**62.5**	129.0								
H1													105.0	**300.0**	75.0	**400.0**	35.0	**100.0**	25.0
H2			185.0	**125.0**	160.0	**5.0**	159.0	**145.0**	130.0	**5.0**	129.0	120.0	105.0	**150.0**	75.0	**200.0**	35.0		
C1	185.0	**212.5**	156.7	**125.0**	140.0	**80.0**	129.3	**145.0**	110.0	**67.5**	101.0	120.0	85.0	**450.0**	25.0				
Cooling															6.0	**600.0**	5.1	**100.0**	5.0

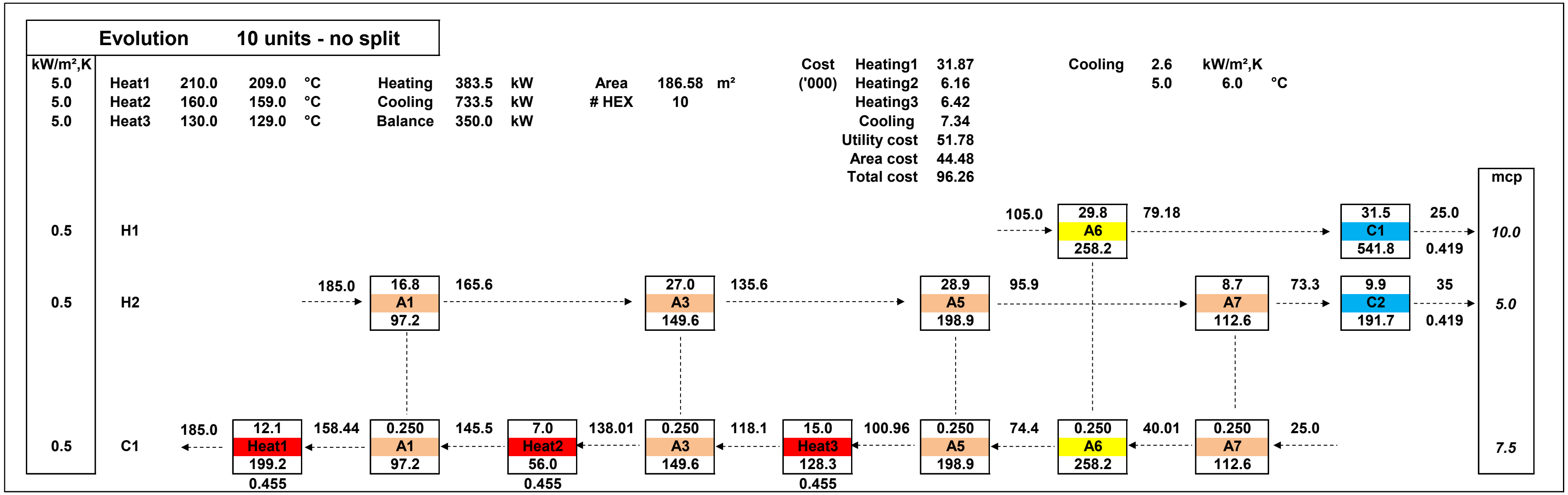
Crisscross

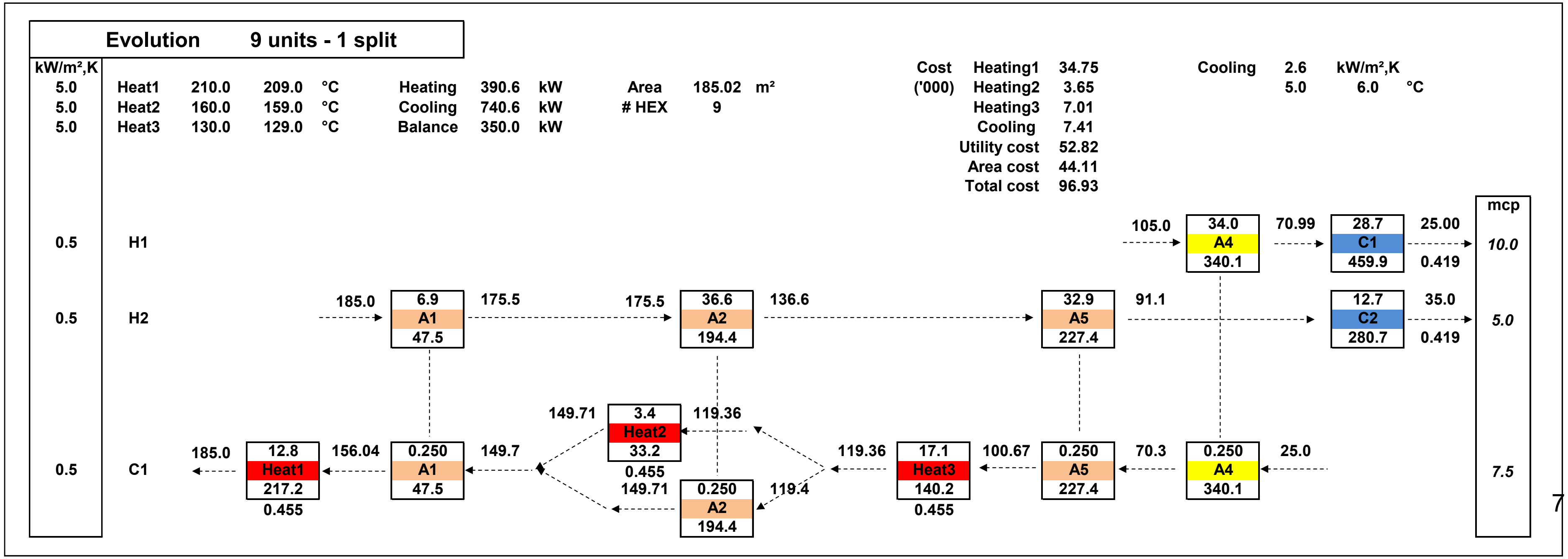
Description		1		2		3		4		5		6		7		8		9	
-	°C	kW	°C	kW	°C	kW	°C	kW	°C	kW	°C	kW	°C	kW	°C	kW	°C	kW	°C
HP Stean	210.0	**199.7**	209.0																
MP Stean					160.0	**55.25**	159.0												
LP Steam									130.0	**122.5**	129.0								
H1													105.0	**281.7**	76.8	**418.3**	35.0	**100.0**	25.0
H2			185.0	**95.0**	166.0	**5.0**	165.0	**145.0**	136.0	**5.0**	135.0	**150.0**	105.0	**140.9**	76.8	**209.2**	35.0		
C1	185.0	**199.7**	158.4	**95.0**	145.7	**60.25**	137.7	**145.0**	118.3	**127.5**	101.3	**150.0**	81.3	**422.6**	25.0				
Cooling															6.0	**627.5**	5.1	**100.0**	5.0

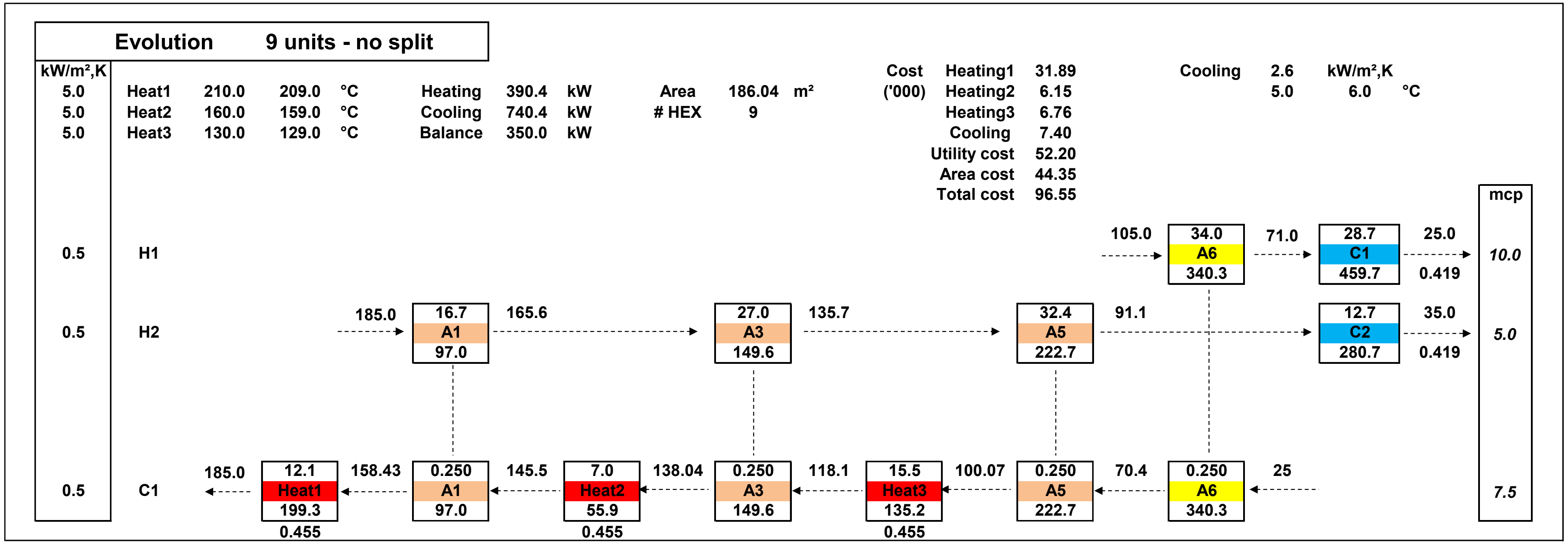
Figures 27.3 Heat Exchanger Networks


Initial network Crisscross


Evolution 10 units - 1 split

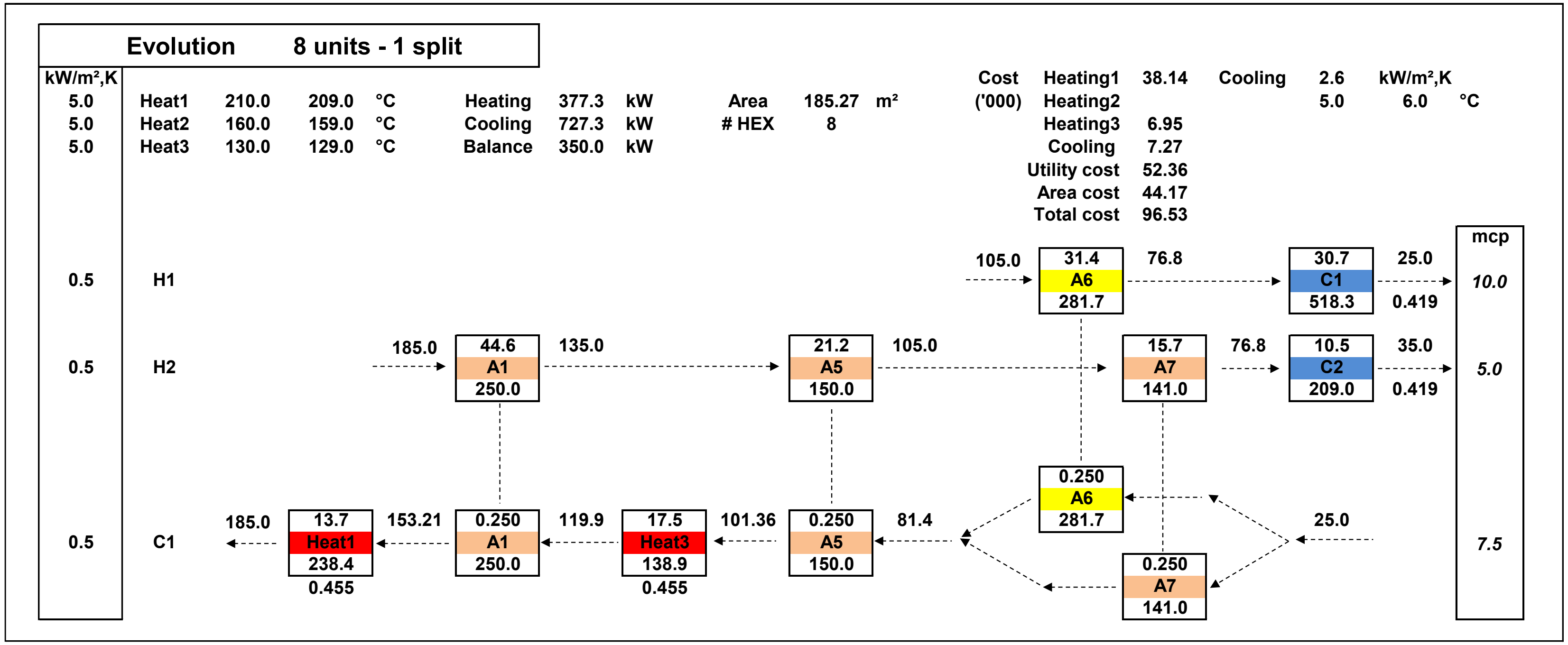

Evolution
10 units - no split
kW/m²,K
5.0
5.0
5.0
Heat1 210.0 209.0 °C
Heat2 160.0 159.0 °C
Heat3 130.0 129.0 °C
Heating 383.5 kW
Cooling 733.5 kW
Balance 350.0 kW
Area 186.58 m²
HEX 10
Cost ('000)
Heating1 31.87
Heating2 6.16
Heating3 6.42
Cooling 7.34
Utility cost 51.78
Area cost 44.48
Total cost 96.26
Cooling 2.6 kW/m²,K
5.0 6.0 °C
mcp
0.5 H1
105.0
29.8 A6 258.2
79.18
31.5 C1 541.8
25.0
0.419
10.0
0.5 H2
185.0
16.8 A1 97.2
165.6
27.0 A3 149.6
135.6
28.9 A5 198.9
95.9
8.7 A7 112.6
73.3
9.9 C2 191.7
35
0.419
5.0
0.5 C1
185.0
12.1 Heat1 199.2
0.455
158.44
0.250 A1 97.2
145.5
7.0 Heat2 56.0
0.455
138.01
0.250 A3 149.6
118.1
15.0 Heat3 128.3
0.455
100.96
0.250 A5 198.9
74.4
0.250 A6 258.2
40.01
0.250 A7 112.6
25.0
7.5


Evolution
9 units - 1 split
kW/m²,K
5.0
5.0
5.0
Heat1 210.0 209.0 °C
Heat2 160.0 159.0 °C
Heat3 130.0 129.0 °C
Heating 390.6 kW
Cooling 740.6 kW
Balance 350.0 kW
Area 185.02 m²
HEX 9
Cost ('000)
Heating1 34.75
Heating2 3.65
Heating3 7.01
Cooling 7.41
Utility cost 52.82
Area cost 44.11
Total cost 96.93
Cooling 2.6 kW/m²,K
5.0 6.0 °C
mcp
0.5 H1
105.0
34.0 A4 340.1
70.99
28.7 C1 459.9
25.00
0.419
10.0
0.5 H2
185.0
6.9 A1 47.5
175.5
175.5
36.6 A2 194.4
136.6
32.9 A5 227.4
91.1
12.7 C2 280.7
35.0
0.419
5.0
0.5 C1
185.0
12.8 Heat1 217.2
0.455
156.04
0.250 A1 47.5
149.7
149.71
3.4 Heat2 33.2
0.455
119.36
149.71
0.250 A2 194.4
119.4
119.36
17.1 Heat3 140.2
0.455
100.67
0.250 A5 227.4
70.3
0.250 A4 340.1
25.0
7.5



Evolution 9 units - no split

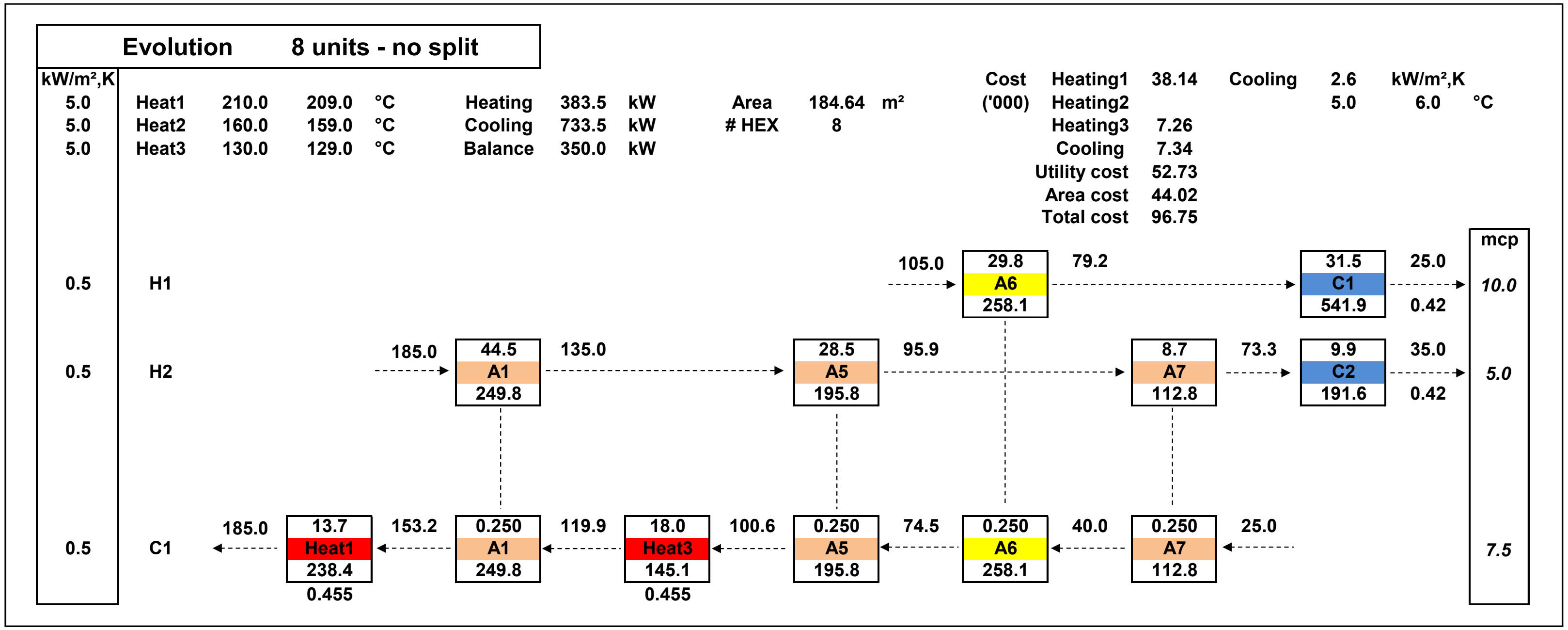
kW/m²,K																
5.0	Heat1	210.0	209.0	°C	Heating	390.4	kW	Area	186.04	m²	Cost ('000)	Heating1	31.89	Cooling	2.6	kW/m²,K
5.0	Heat2	160.0	159.0	°C	Cooling	740.4	kW	# HEX	9			Heating2	6.15		5.0	6.0 °C
5.0	Heat3	130.0	129.0	°C	Balance	350.0	kW					Heating3	6.76			
												Cooling	7.40			
												Utility cost	52.20			
												Area cost	44.35			
												Total cost	96.55			



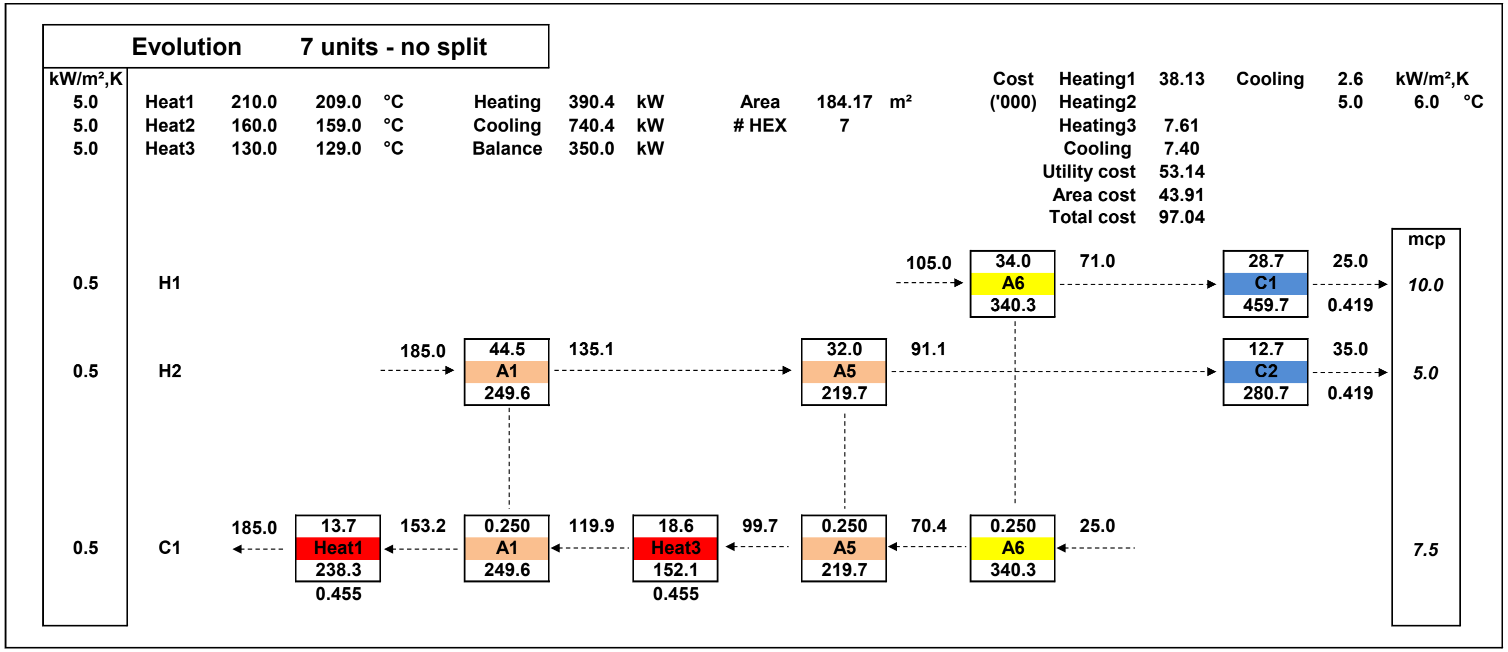
Evolution 8 units - 1 split

kW/m²,K																
5.0	Heat1	210.0	209.0	°C	Heating	377.3	kW	Area	185.27	m²	Cost ('000)	Heating1	38.14	Cooling	2.6	kW/m²,K
5.0	Heat2	160.0	159.0	°C	Cooling	727.3	kW	# HEX	8			Heating2			5.0	6.0 °C
5.0	Heat3	130.0	129.0	°C	Balance	350.0	kW					Heating3	6.95			
												Cooling	7.27			
												Utility cost	52.36			
												Area cost	44.17			
												Total cost	96.53			

Evolution 8 units - no split



Evolution 7 units - no split



Example 2

The second example has 2 hot streams, 3 cold streams, 3 hot utilities and 2 cold utilities. It was used by the same authors as Example 1 and further by Liu et al. [8] and Martelli et al. [9].

The data set is shown in Table 27.9, cost figures in Table 27.10.

Table 27.9

Tsupply	Ttarget	Heat	Shift	U*f	Descrip	mcp
°C	°C	kW	K	kW/m²,K	-	kW/K
155	85	10500	7.5	0.5	H1	150.0
230	40	16150	7.5	0.5	H2	85.0
115	210	13300	7.5	0.5	C1	140.0
50	180	7150	7.5	0.5	C2	55.0
60	175	6900	7.5	0.5	C3	60.0
255	254			0.5	HP Steam	
205	204			0.5	MP Steam	
150	149			0.5	LP Steam	
30	40			0.5	Cooling Water	
40	65			0.5	Air Cooling	

Table 27.10

Utility costs		Capital cost		
	$/kW,year	HEX area	800 $/m²	
HP Steam	70.0	annuiity	0.298	
MP Steam	50.0	Cost/year	238.4 $/m²,year	
LP Steam	20.0			
Cooling Water	10.0			
Air Cooling	5.0			

For a first indication, the analysis with a global DTMin of 15 K generates the Composite Curves of Figure 27.4; required heating is 8225 kW; the pinch is caused by cold stream C1. The Grand Composite in Figure 27.5 does not suggest specific loads for HP-, MP- or LP steam. Further, only Cooling Water will be used so far since the choice between Cooling Water and Air Cooling can be made in a final design stage.

A trade-off with only HP Steam and Cooling water results in 8030 kW heating for a cost of 1194.96 k$/year. A trade-off with only MP Steam results in 8390 kW heating for a cost of 1132.60 k$/year, MP steam appearing to be a valuable component to cover the heating demand. A trade-off with a combination of MP-and LP Steam suggests that use of LP Steam is not attractive. A final trade-off can be made now with a step-by-step approach as described for Example 1. The distribution between the Steam loads at the start can, in principle, be chosen at random; however, since the cost with using only MP Steam is lower than the cost with only HP Steam, more MP Steam and less HP steam would foster the convergence process. To start the procedure, a certain MP Steam load is chosen and a trade-off HP Steam versus Capital cost is made to find a new load for the HP Steam. With that new value, a trade-off MP Steam versus Capital cost is made to find a new load for the MP Steam. This procedure is repeated until convergence is reached. The results for a pinched system (the targets) are 1500 kW HP Steam, 6980 kW MP Steam and 7780 kW Cooling Water, an area of 4964.4 m², 10 units and a cost of 1130 k$/year. Targets for a system with only HP Steam are 8030 kW HP Steam heating and 7330 kW Cooling Water, an area of 4698.0 m², 9 units and a cost of 1194.96 k$/year. Targets for a system with only MP Steam are 8390 kW MP Steam heating and 7690 kW Cooling Water, an area of 5561.9 m², 9 units and a cost of 1132.60 k$/year. A similar analysis can also be done for a single system with the following targets: 1400 kW HP Steam, 6970 kW MP Steam and 7670 kW Cooling Water, an area of 5060.0 m², 7 units and a cost of 1084.57 k$/year.

Various networks have been designed, the best of which are listed in Table 27.11, together with the results found in literature, most of which had to be revised with correct LMTD calculations. The designed networks are shown in Figures 27.6 through 27.12. A network with only HP Steam was not withheld since that was not competitive, as could already be expected from the analysis.

Starting with the network of Figure 27.10, application of a smart node as explained in [10] on the split on hot stream H1 leads to the network of Figure 27.11 which is like the network from Huang & Karimi, apart from some minor improvements. The same smart node can be applied in the network of Figure 27.7, Figure 27.8 and Figure 27.9, with a similar marginal saving of 157 $/year. In view of this small amount, however, this measure might not be preferred for reasons of operability and control.

Table 27.11	HP Steam	MP Steam	Total Steam	Air Cooling	Cooling Water	# HEX	# splits	Area	Cost
	kW	kW	kW	kW	kW	-	-	m²	k$/year
Shenoy et al. °)	4885.0	3575.0	8460.0	3600.0	4160.0	9	1	5044.7	1158.23
Isafiade & Frazer °)	5928.5	1852.0	7780.5	-	7080.5	7	1	5426.2	1146.84
Ponce-Ortega et al.°)	4290.0	4075.3	8365.3	-	7665.3	8	1	4888.0	1118.00
Huang & Karimi °)	4186.4	4060.3	8246.7	-	7546.7	8	1	4994.0	1116.64
Na et al. °)	4228.6	4083.1	8311.7	533.1	7078.6	8	1	187.11	1117.54
Martelli et al. °)	4228.7	4098.0	8326.7	548.0	7078.7	8	1	4953.1	1118.03
Liu et al. °)	4230.5	4110.8	8341.3	-	7641.3	8	1	4917.7	1117.58
Yang et al.	4228.64	4069.67	8298.3	-	7598.30	8	1	4943.2	1116.85
°) revised									
This work									
Targeting	1500	6980	8480	-	7780	10	-	4964.4	1130.00
	8030	-	8030		7330	9	-	4698.0	1194.96
	-	8390	8390		7690	9	-	5561.9	1132.60
	1400	6970	8370	-	7670	7	-	5060.0	1084.57
Design	-	8351	8351	3420	4231	9	1	5877.5	1136.40
	-	8412	8412	-	7712	9	1	5737.6	1130.54
	1510	6886	8396	-	7696	10	1	5212.1	1120.80
	2919	5417	8336	-	7636	9	1	5100.5	1120.03
	4197	4063	8260	-	7560	8	1	4981.4	1116.79
	4197	4062	8259	-	7559	8	1	4981.2	1116.63
	4197	3550	7747	-	7047	7	1	5526.7	1121.70

.

In case of multiple utilities, a trade-off based on DTMIN does not lead to satisfactory results. Using the above examples, a procedure has been demonstrated for a trade-off between energy and capital using heating loads as parameters. Also, the case with different heat transfer coefficients can be handled properly.

Figure 27.4

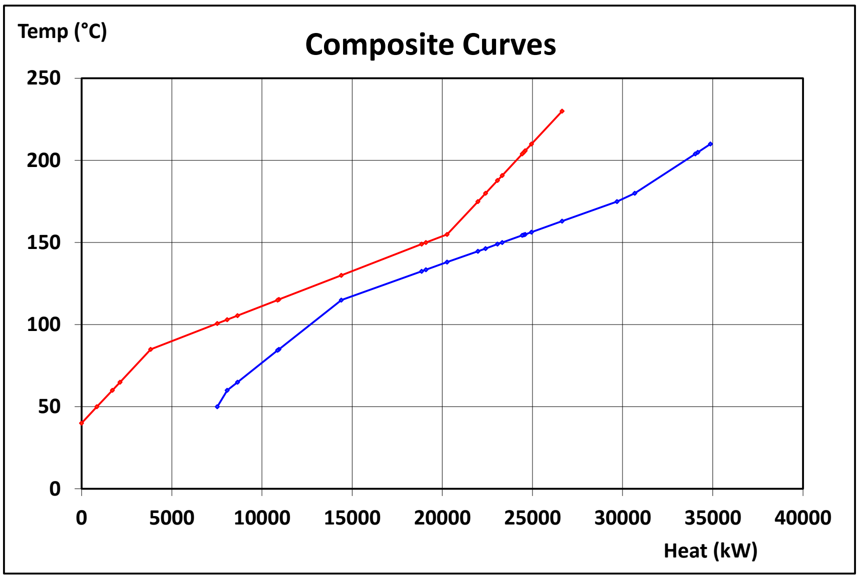


Figure 27.5

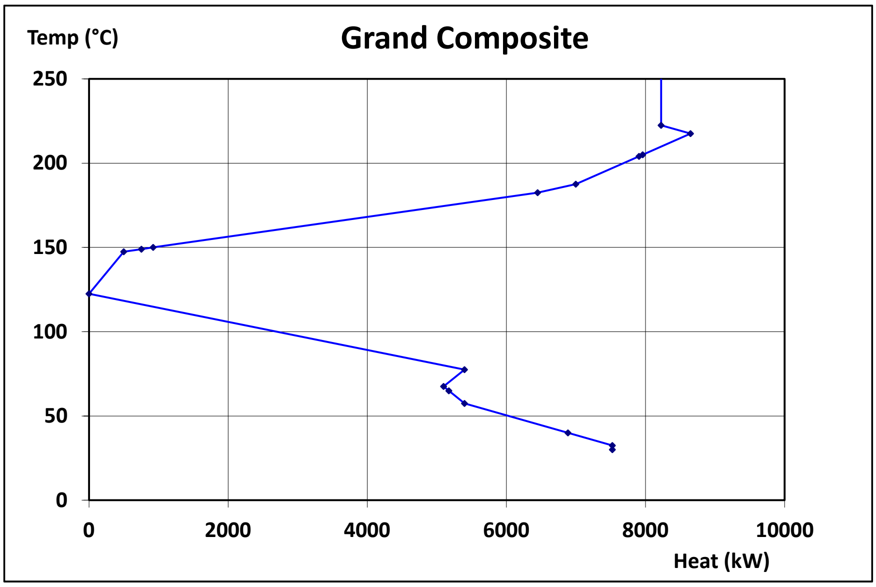


Figure 27.6

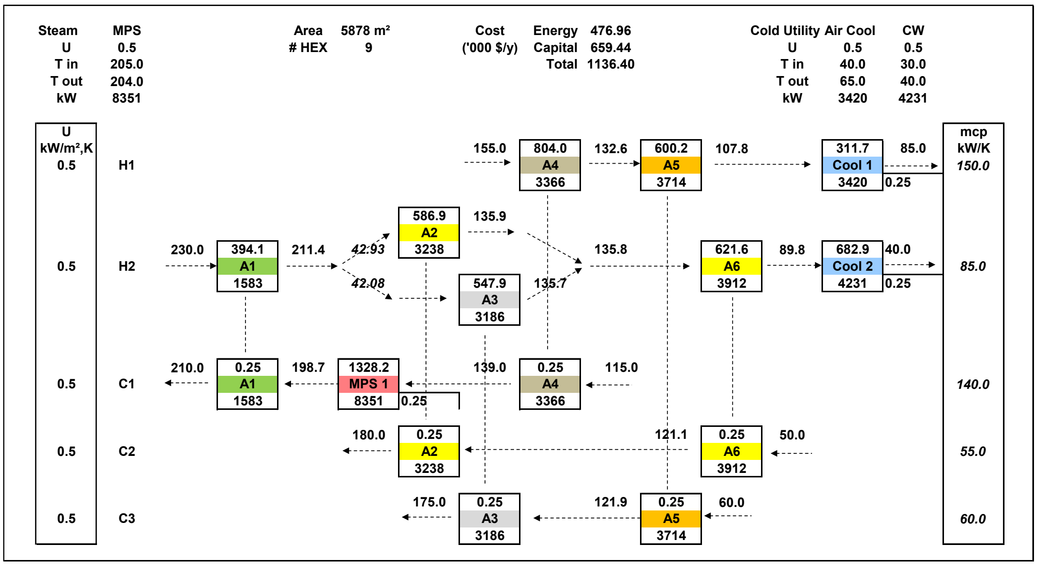


Figure 27.7

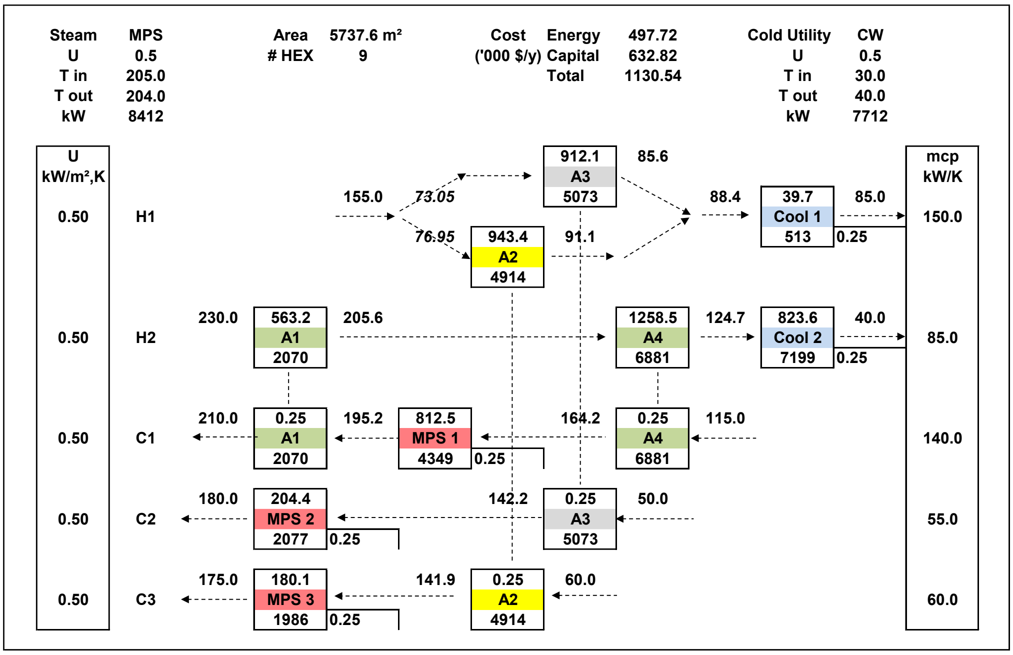


Figure 27.8

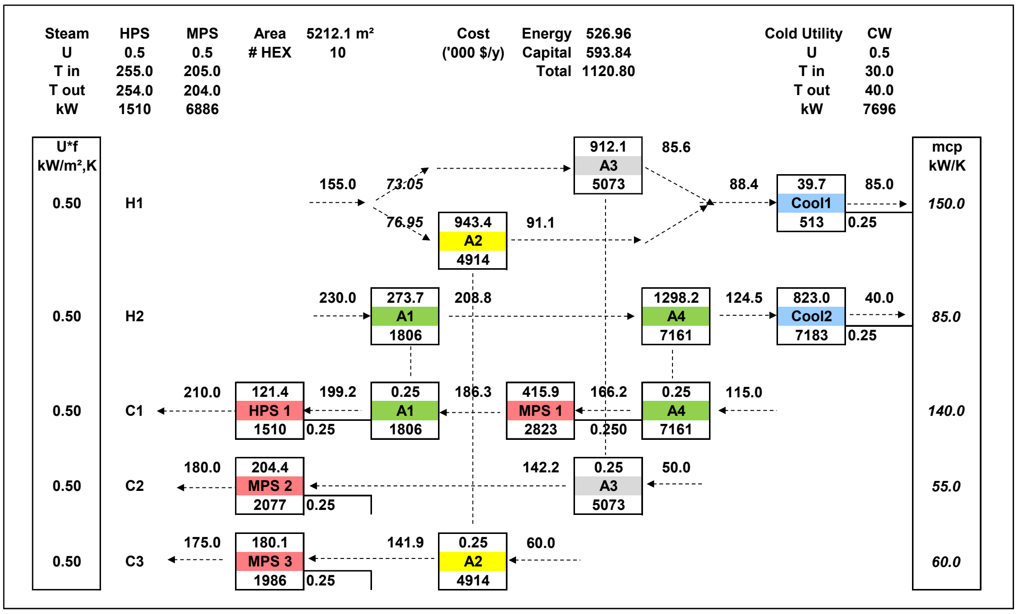


Figure 27.9

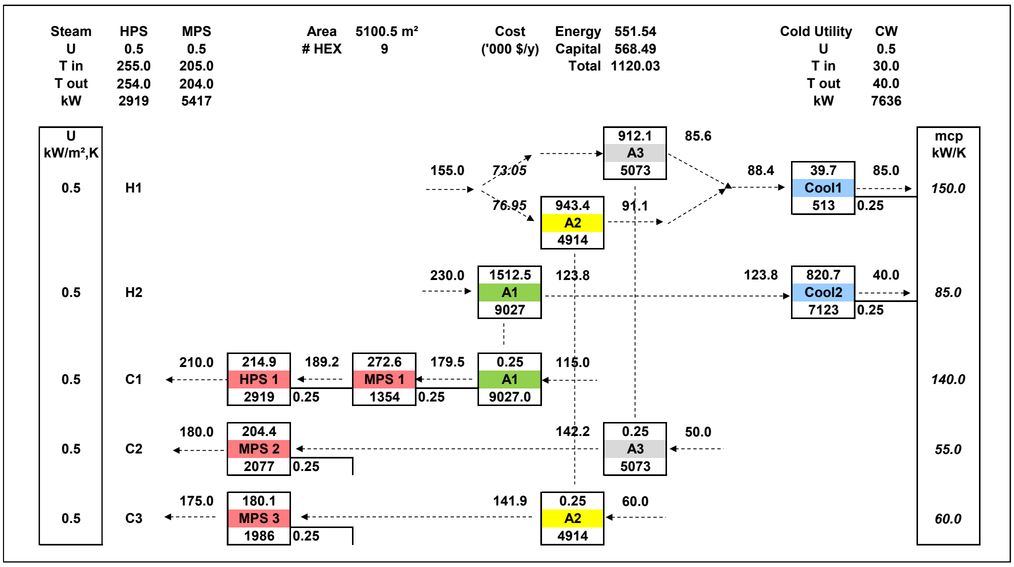


Figure 27.10

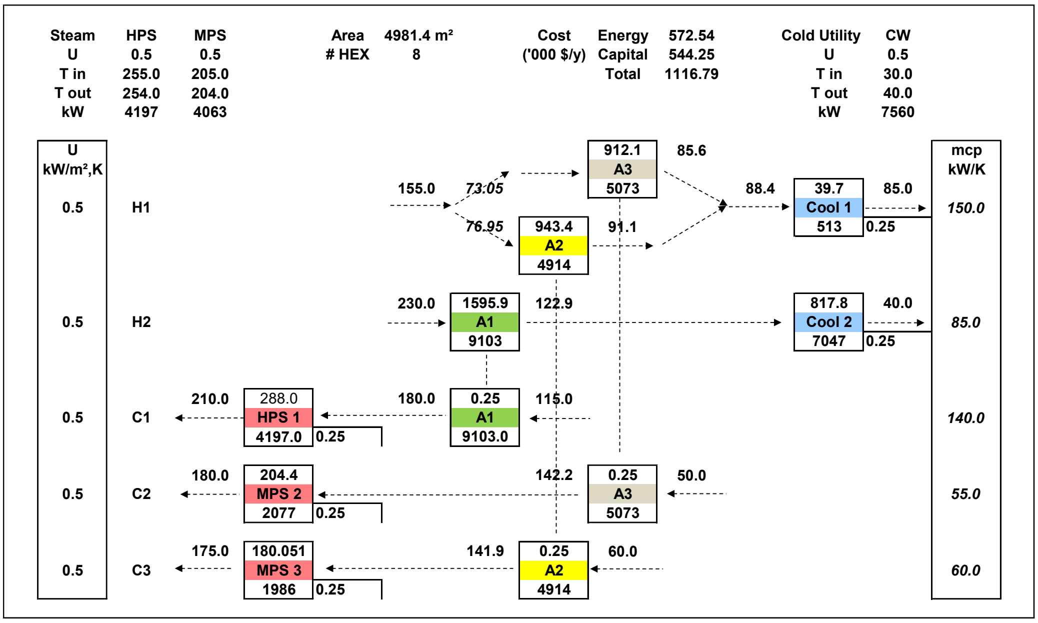


Figure 27.11

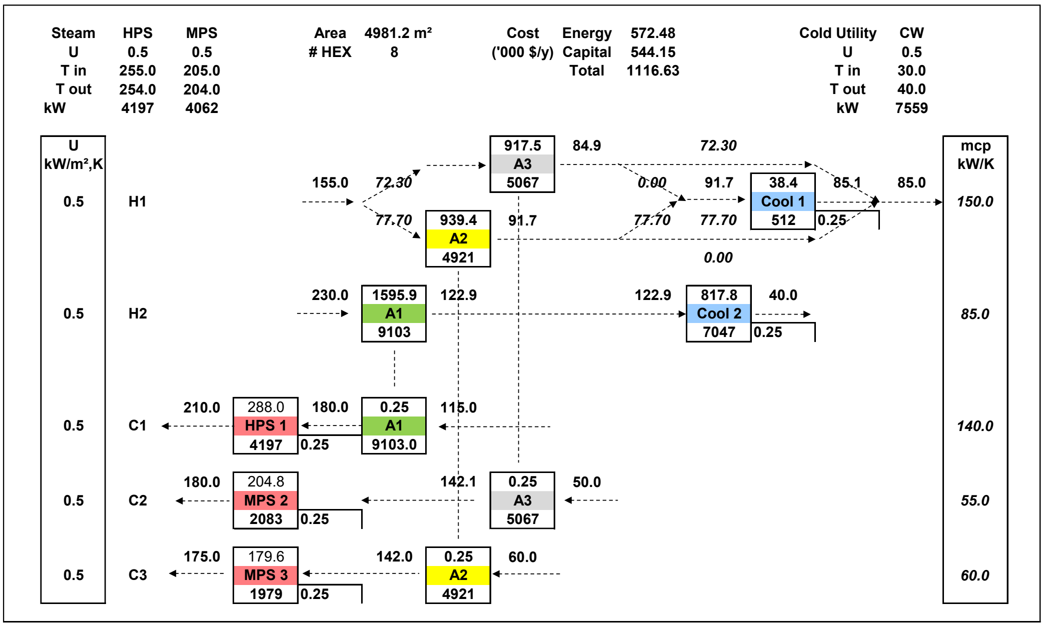
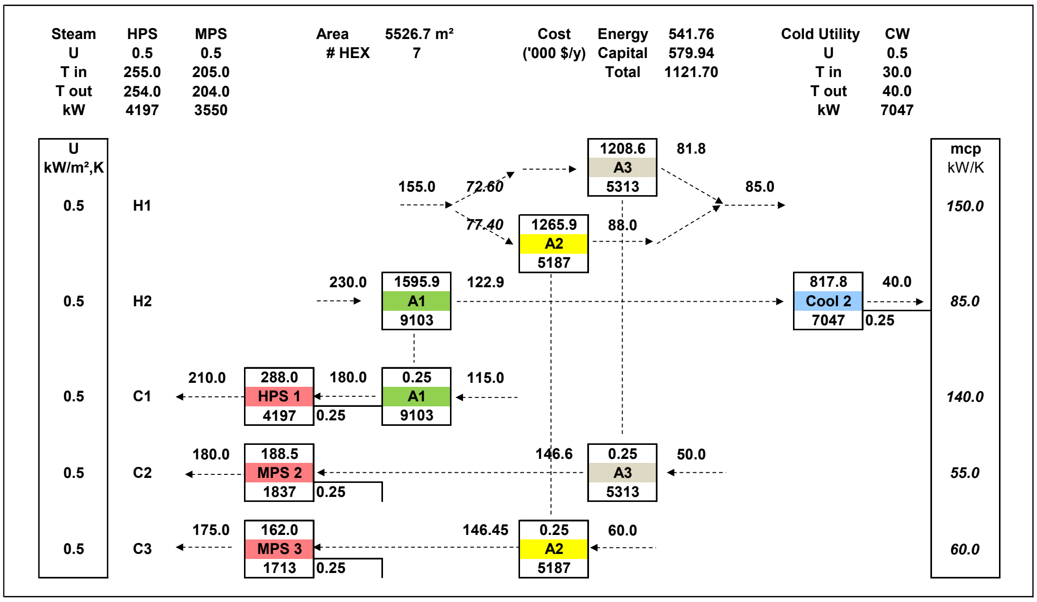


Figure 27.12



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