The importance of targeting in heat exchanger network synthesis.
Case 25 - The Example from Faria, Kim and Bagajewicz

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The original data set of this 9 streams example was reported as 10SP1 by Cerda [1] and treated also by Papoulias and Grossmann [2] in the early eighties. It was studied by Faria et al. in 2015 [3], by Kim and Bagajewicz in 2016 [4] and by Nair et al. in 2019 [5].

Stream data and financial parameters are given in Table 25.1.

Table 25.1

Tsupply	Ttarget	Heat	DT-shift	U*f	Descript.	mcp
K	K	kW	K	kW/K,m²	-	kW/K
500.15	339.15	713.39	5	0.06	H1	4.431
472.15	339.15	707.43	5	0.06	H2	5.319
522.15	411.15	350.98	5	0.06	H3	3.162
433.15	366.15	176.48	5	0.06	H4	2.634
355.15	450.15	492.48	5	0.06	C1	5.184
366.15	478.15	467.04	5	0.06	C2	4.170
311.15	494.15	463.36	5	0.06	C3	2.532
333.15	433.15	228.6	5	0.06	C4	2.286
389.15	495.15	193.34	5	0.06	C5	1.824
544.15	422.15		5	0.06	Heating	
311.15	355.15		5	0.06	Cooling	

Financial parameters			
Heating :	566 167	$/kW,year	
Cooling :	53 349	$/kW,year	
HEX-unit cost : 5 291.9 + 77.8*Area			$/year

A minimum value of 10 K as EMAT (exchanger minimum approach temperature) is imposed. Specific for this example is the extremely high utilities cost that is some 2500 times the normal cost; the origin of this high level could not be tracked down nor explained.

Results of the Pinch Analysis are given in Table 25.2. The composite curves are shown in Figure 25.1. The curves are parallel over a wide range; the pinch is caused by cold stream C2

Table 25.2

Pinch Temperature THot/Tcold streams (K):			376.15	366.15
Pinch caused by stream N#			6	Cold stream
Minimum Heating / Cooling (kW) :			11.908	115.368
Feasible # units above/below Pinch :			9	6
		Total	Above	Below Pinch
HEX area :	m²	4137.96	3269.35	868.61
Cost Utilities :	*000 $/y	12896.50	6741.75	6154.75
Cost Investment :	*000 $/y	401.27	301.95	99.32
Total Cost :	*000 $/y	13297.77		

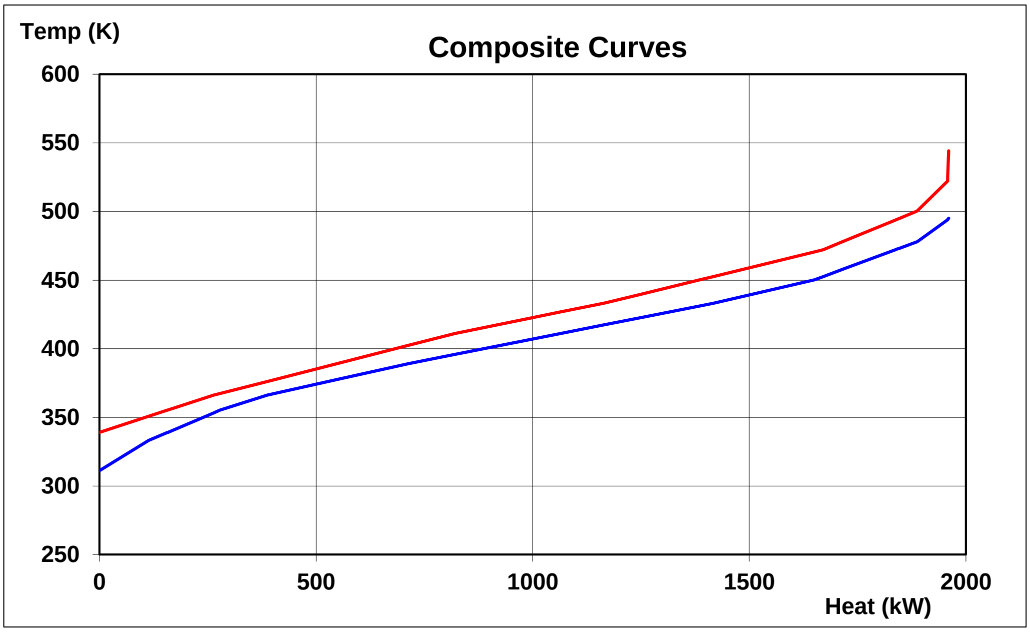


Figure 25.1

The analysis further indicates that the problem can be turned into a threshold problem (without heating) if an EMAT of 9.0385 K is applied. In view of the extremely high energy cost, this alternative is certainly worth being further explored.

Three alternative routes have been worked out.
First, a grid diagram was generated using the pinch analysis tool, resulting in a scheme with 16 integration bands. A design with an LP program generated a network satisfying energy and area targets, however, with 83 heat exchanger units; that number had to be reduced. To simplify the task, the number of integration bands was reduced from 16 to 7 by merging adjacent bands, without significantly changing the nature of the problem (Table 25.3).

Table 25.3 – Reduced Grid diagram

Descript.	Heat	mcp					Pinch			
-	kW	kW/K	1	2	3	4	5	6	7	
Heating	11.908	0.10	544.15	500.87	472.15	422.15				
H1	713.39	4.43		500.15	472.15	411.15	376.15	367.27	350.78	339.15
H2	707.43	5.32			472.15	411.15	376.15	367.27	350.78	339.15
H3	350.98	3.16	522.15	500.87	472.15	411.15				
H4	176.48	2.63				433.15	376.15	366.15		
C1	492.48	5.18			450.15	400.82	366.15	355.15		
C2	467.04	4.17		478.15	452.62	400.82	366.15			
C3	463.36	2.53	494.15	478.15	452.62	400.82	366.15	353.99	333.15	311.15
C4	228.60	2.29			433.15	400.82	366.15	355.15	333.15	
C5	193.34	1.82	495.15	478.15	452.62	389.15				
Cooling	115.368	2.62						355.15	333.15	311.15

Application of LP on the reduced diagram generated a network with 34 units and an area of 4342.38 m², some 5% above the minimum target area. This was the initial network for further evolution in the 1st route.

To simplify the task ahead of applying LP, as suggested by heuristics [6], in a 2nd route, a heater was imposed on a branch of cold stream C2, fitting into the grid diagram and cold stream C5 was matched with a branch of hot stream H3. The remaining problem was further processed as in the 1st route.

In the 3rd route, a heater was imposed on a branch of cold stream C5, fitting into the grid diagram and the other branch of C5 was matched with a branch of hot stream H3. The remaining problem was processed as in the first route.

Obviously, inspection of the grid diagram might suggest other matches.

Evolution of the networks enables cost reduction by elimination of heat exchanger units. In this process, the imposed EMAT of 10 K was maintained. The following techniques were applied for optimisation as explained in earlier papers, [6] a.o.:

- introduction of non-isothermal splits,
- development by incremental evolution,
- distortion of the solution space,
- use of smart nodes.

When the above techniques were exhausted, then swaps between HEX units in a same integration band were explored to remove EMAT constraints and, if successful, the optimisation techniques were repeated. Finally, split configurations and splits were analysed where they had led to EMAT constraints and eventually optimised.

The initial network of route 1 had a heater on cold stream C2 and a smaller heater on cold steam C5. After evolution, there was 1 heater left on C2.

Evolution in route 2 led to the same network with the heater on cold stream C2.

Route 3 with a heater on cold stream C5 led to a network with a quite similar structure. Differences between the two networks are:

- the location of the heater,
- the load distribution among the heat exchanger units,
- the split ratios.

Both networks fully satisfy the energy targets. The network with the heater on cold stream C5 has the lowest cost (13318.07 k$/year); the difference with the other network, however, is marginal (less than 700$). The networks are shown in Figure 25.3 and in Figure 25.4.

Various types of splits as shown in Figure 25.2 were investigated for the first split in hot stream H1; related to the investment cost, the differences with the optimum split are less than 0.07% for route 1 and less than 0.009% for route 3.

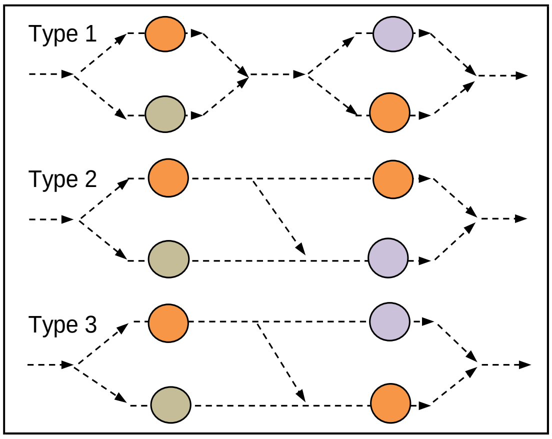


Figure 25.2

After synthesising the networks for a heating load of 10.908 kW, these networks were further developed into the threshold case with no heating; this led to a single optimum solution with a total cost of 5955.09 k$/year. This network is shown in Figure 25.5.

The results regarding investment costs are summarised in Table 25.4. Energy costs are not reported here since on target for all cases.

Table 25.4 - Results

Heater on C2 - 17 units - 12 splits				
split type		3	1	2
Surface	m²	4 272	4 273	4 275
Area cost	'000 $	422.26	422.34	422.55

Heater on C5 - 17 units - 12 splits				
split type		3	2	1
Surface	m²	4 263	4 263	4 263
Area cost	'000 $	421.57	421.60	421.61

No heating - 16 units - 12 splits				
split type		2	3	1
Surface	m²	4 511	4 512	4 512
Area cost	'000 $	435.61	435.66	435.68

The annual costs of the best network (heater on cold stream C5 and split type 3) are compared with results from literature in Table 25.5. Threshold networks have not been reported in literature.

Table 25.5

Comparison								
	Heating	Cooling	Area	Energy cost	Capital Cost	Total cost	# units	# splits
DTMin 10 K								
	kW	kW	m²	'000 $/y	'000 $/y	'000 $/y	-	-
Targets	11.908	115.368	4 138	12 896.50	401.27	13 297.77	15	-
Faria et al.	151.39	254.85	3 067	99 309.25	296.78	99 606.03	11	1
Nair et al.	42.681	146.14	5 008	31 961.00	458.29	32 419.29	13	12
This study	11.908	115.368	4 263	12 896.50	421.57	13 318.07	17	12
DTMin 9.0385 K								
Targets	0.00	103.46	4 369	5 519.49	413.92	5 933.41	14	-
This study	0.00	103.46	4 511	5 519.49	435.61	5 955.09	16	12

The cost of the best network with an EMAT of 10 K is less than 14% of the cost of the network in [3] and 58.9 % lower than the cost of the best network published so far. With an EMAT of 9.0385 K, no heating is required and the cost can drop further with another 55%.

The initial network based on the original grid is not unique but depends upon the sequence of the streams as input for the LP application. A different sequence will generate a similar grid but a different initial network with the same area and area cost but with a different distribution of the loads on the heat exchanger units in the integration bands. With 144 possible permutations in the sequences, there are as many different initial networks, each of which could develop into a network, different from the networks presented here.

Literature.

[1] Cerda, J. Transportation models for the optimal synthesis of heat exchanger networks. Ph.D. Thesis. Carnegie-Melon University: Pittsburgh, PA, 1980.

[2] Papoulias, S. A.; Grossmann, I. E. A structural optimization approach in process synthesis-II: Heat recovery networks. Comput.Chem. Eng. 1983, 7 (6), 707−721.

[3] Faria, D. C.; Kim, S. Y.; Bagajewicz, M. J. Global Optimization of the Stage-wise Superstructure Model for Heat Exchanger Networks. Ind. Eng. Chem. Res. 2015, 54 (5), 1595−1604.

[4] Kim, S. Y.; Bagajewicz, M. Global optimization of heat exchanger networks using a new generalized superstructure. Chem. Eng. Sci. 2016, 147, 30−46.

[5] Sajitha K. Nair and Iftekhar Karimi, Ind. Eng. Chem. Res. DOI: 10.1021/acs.iecr8b04490, February 1, 2019.

[6] Case 21 – Synthesis of Heat Exchanger Networks – Smart optimisation procedures
DOI: 10.13140/RG.2.2.26429.51683

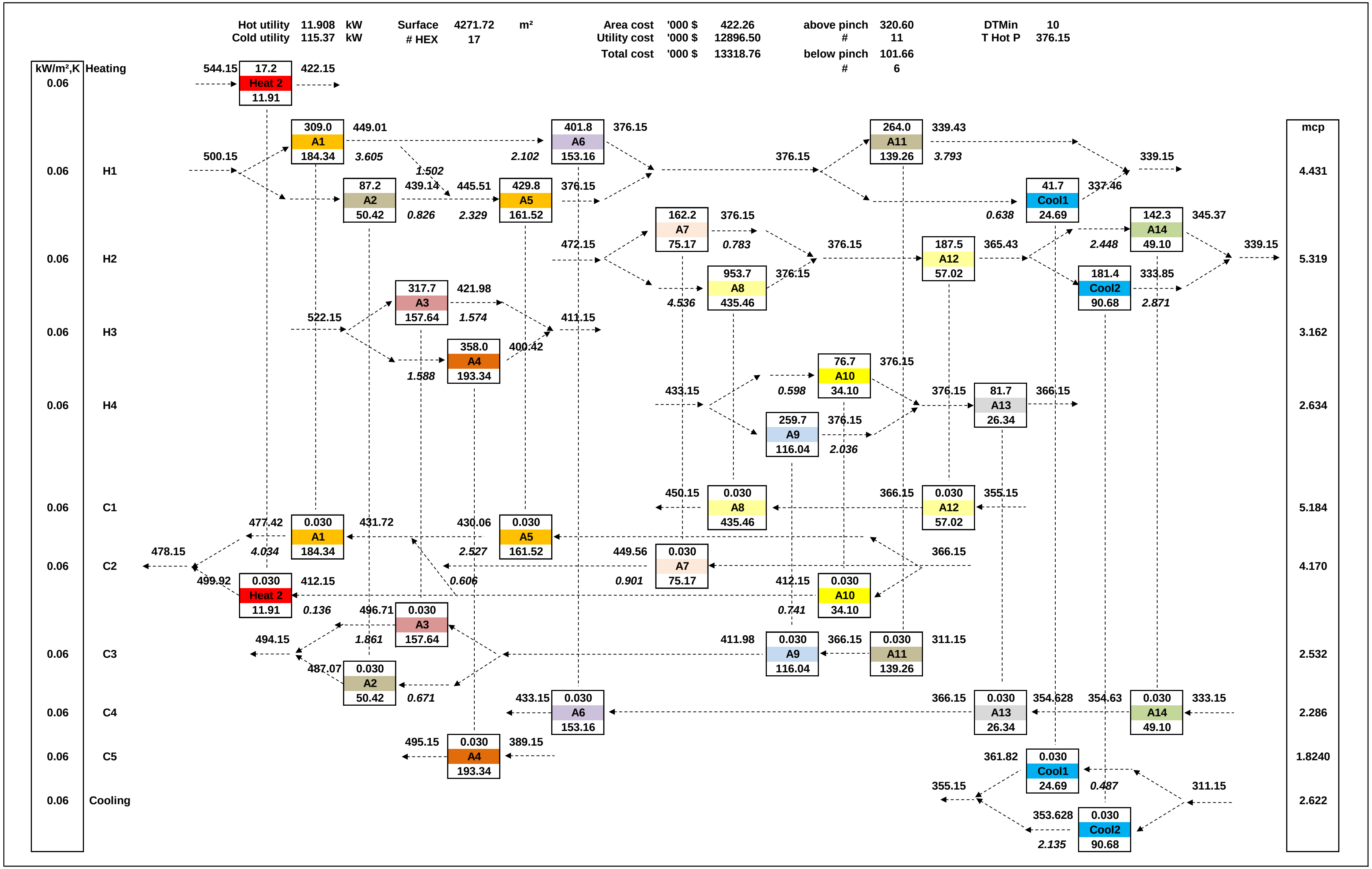
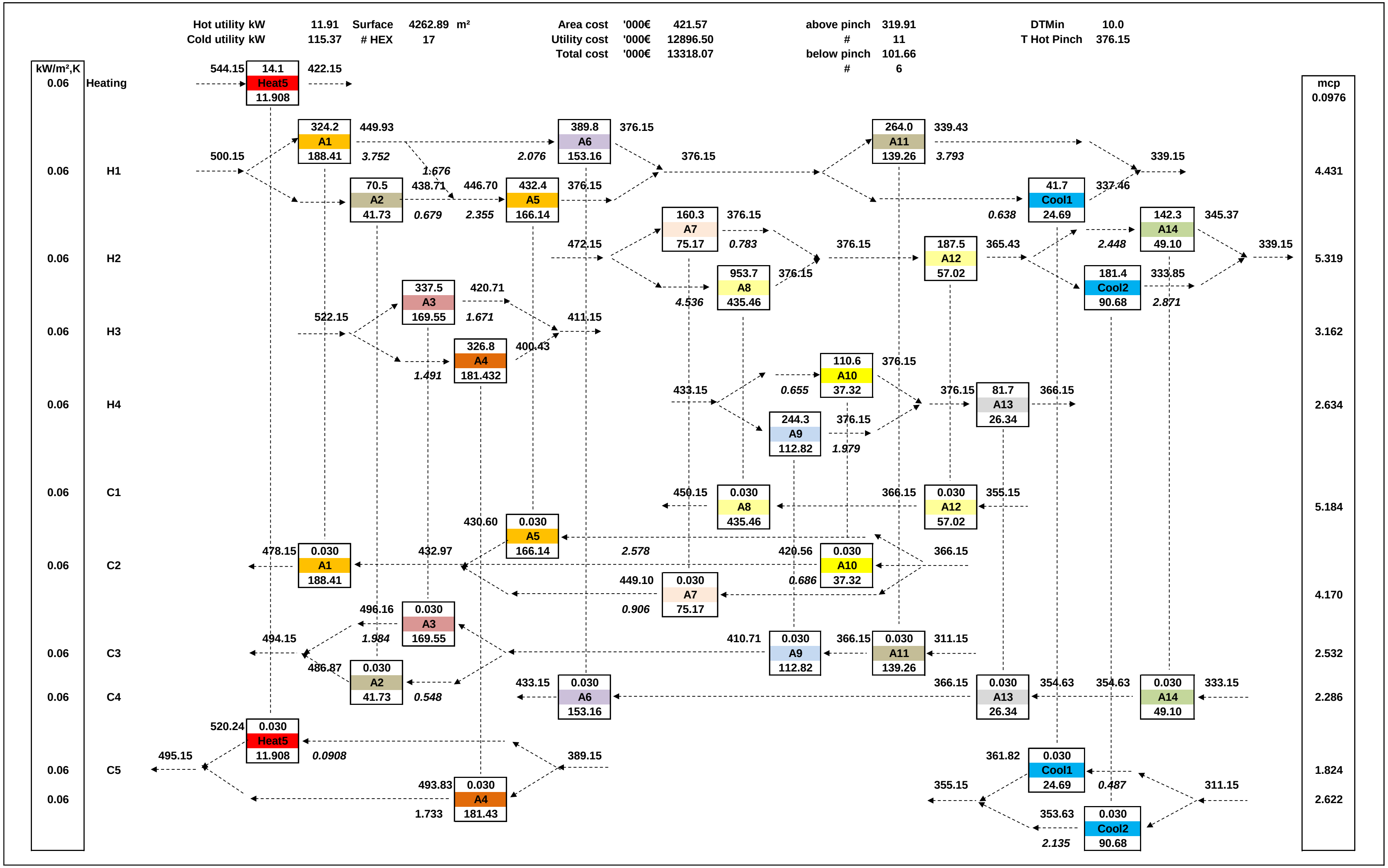
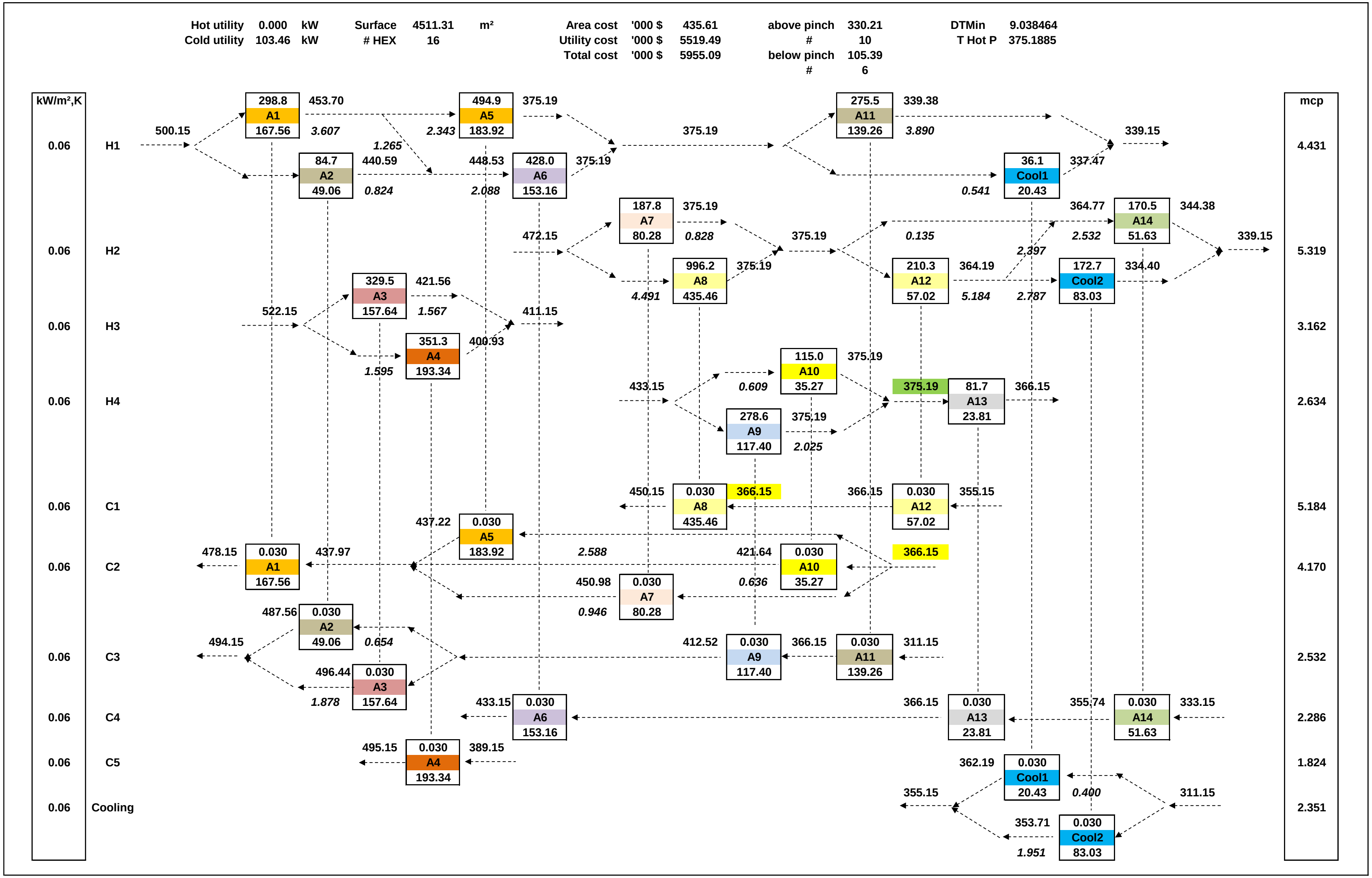

Hot utility 11.908 kW
Cold utility 115.37 kW
Surface 4271.72 m²
HEX 17
Area cost '000 $ 422.26
Utility cost '000 $ 12896.50
Total cost '000 $ 13318.76
above pinch 320.60
11
below pinch 101.66
6
DTMin 10
T Hot P 376.15
kW/m²,K
Heating
0.06
H1
H2
H3
H4
C1
C2
C3
C4
C5
Cooling
mcp
4.431
5.319
3.162
2.634
5.184
4.170
2.532
2.286
1.8240
2.622
544.15
17.2
Heat 2
11.91
422.15
500.15
309.0
A1
184.34
449.01
3.605
401.8
A6
153.16
376.15
2.102
1.502
87.2
A2
50.42
439.14
445.51
429.8
A5
161.52
0.826
2.329
264.0
A11
139.26
339.43
3.793
339.15
41.7
Cool1
24.69
337.46
0.638
162.2
A7
75.17
0.783
472.15
953.7
A8
435.46
4.536
187.5
A12
57.02
365.43
142.3
A14
49.10
345.37
2.448
181.4
Cool2
90.68
333.85
2.871
317.7
A3
157.64
421.98
1.574
522.15
411.15
358.0
A4
193.34
400.42
1.588
76.7
A10
34.10
0.598
433.15
81.7
A13
26.34
366.15
259.7
A9
116.04
2.036
450.15
0.030
355.15
477.42
431.72
430.06
4.034
2.527
478.15
449.56
0.901
499.92
412.15
0.136
0.606
0.741
496.71
494.15
1.861
411.98
311.15
487.07
0.671
433.15
354.628
354.63
333.15
495.15
389.15
361.82
0.487
353.628
2.135

Figure 25.3



Hot utility kW 11.91
Cold utility kW 115.37
Surface 4262.89 m²
HEX 17
Area cost '000€ 421.57
Utility cost '000€ 12896.50
Total cost '000€ 13318.07
above pinch 319.91
11
below pinch 101.66
6
DTMin 10.0
T Hot Pinch 376.15
kW/m²,K
mcp
0.0976
Heating
H1
H2
H3
H4
C1
C2
C3
C4
C5
Heat5
A1
A2
A3
A4
A5
A6
A7
A8
A9
A10
A11
A12
A13
A14
Cool1
Cool2

Figure 25.4


Hot utility 0.000 kW
Cold utility 103.46 kW
Surface 4511.31 m²
HEX 16
Area cost '000 $ 435.61
Utility cost '000 $ 5519.49
Total cost '000 $ 5955.09
above pinch 330.21
10
below pinch 105.39
6
DTMin 9.038464
T Hot P 375.1885
kW/m²,K
mcp
0.06 H1 4.431
0.06 H2 5.319
0.06 H3 3.162
0.06 H4 2.634
0.06 C1 5.184
0.06 C2 4.170
0.06 C3 2.532
0.06 C4 2.286
0.06 C5 1.824
0.06 Cooling 2.351
500.15
298.8 A1 167.56
453.70
3.607
494.9 A5 183.92
2.343
375.19
1.265
84.7 A2 49.06
440.59
0.824
448.53
428.0 A6 153.16
2.088
375.19
375.19
275.5 A11 139.26
339.38
3.890
339.15
36.1 Cool1 20.43
337.47
0.541
187.8 A7 80.28
375.19
0.828
472.15
996.2 A8 435.46
375.19
4.491
375.19
0.135
364.77
170.5 A14 51.63
344.38
2.532
339.15
2.397
210.3 A12 57.02
364.19
5.184
2.787
172.7 Cool2 83.03
334.40
522.15
329.5 A3 157.64
421.56
1.567
411.15
351.3 A4 193.34
400.93
1.595
115.0 A10 35.27
375.19
433.15
0.609
375.19
81.7 A13 23.81
366.15
278.6 A9 117.40
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366.15
0.030 A12 57.02
355.15
437.22
0.030 A5 183.92
478.15
0.030 A1 167.56
437.97
2.588
421.64
0.030 A10 35.27
366.15
450.98
0.030 A7 80.28
0.946
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487.56
0.030 A2 49.06
494.15
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0.030 A3 157.64
1.878
433.15
0.030 A6 153.16
366.15
0.030 A13 23.81
355.74
0.030 A14 51.63
333.15
495.15
0.030 A4 193.34
389.15
362.19
0.030 Cool1 20.43
0.400
311.15
355.15
353.71
0.030 Cool2 83.03
1.951

Figure 25.5