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 by Cerda [1]. It was studied by Faria et al. in 2015 [2], by Kim and Bagajewicz in 2016 [3] and by Nair et al. in 2019 [4].

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		

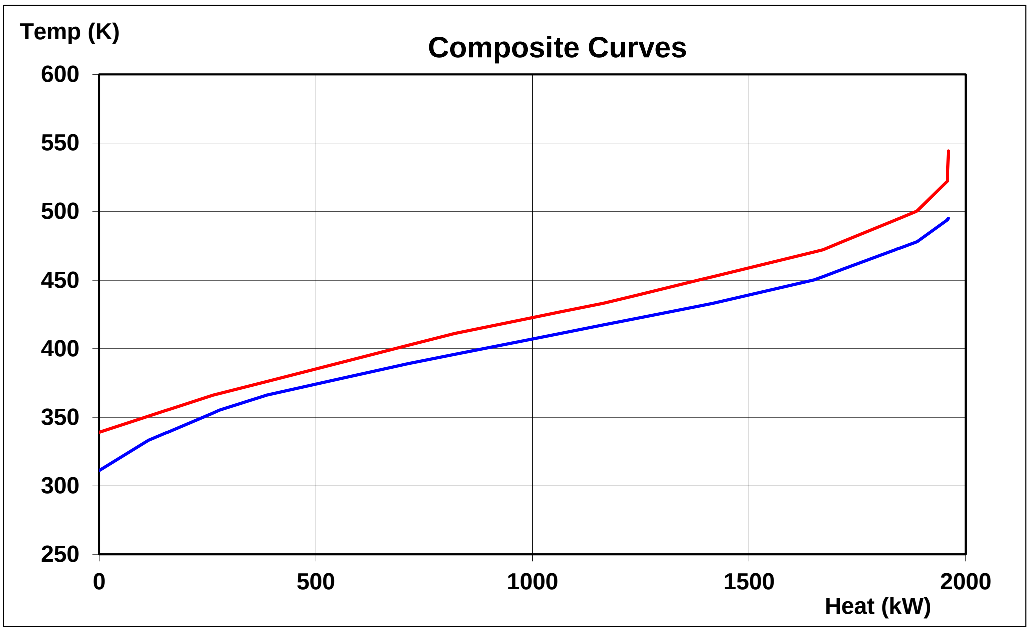

Figure 25.1

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.

a) First route.

A grid diagram is generated using the pinch analysis tool, resulting in a scheme with 16 integration bands. A design with an LP program generates a network satisfying energy and area targets, however, with 83 heat exchanger units; that number should be reduced. To simplify the task, the number of integration bands is 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	Bands														
-	kW	kW/K		1		2		3		4	Pinch	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 generates a network with 34 units and an area of 4342.38 m², some 5% above the minimum target area. This is the initial network for further evolution in the first route.

b) Second route.

To simplify the task ahead of applying LP, in a second route, as suggested by heuristics (satisfy the smallest heat load with 1 exchanger unit), a heater is imposed on a branch of cold stream C5 and the other branch of C5 is matched with a branch of hot stream H3. The remaining problem is processed as in the first route.

c) Third route.

In a third route, cold stream C5 is matched with a branch of hot stream H3, and a heater is imposed on a branch of cold stream C2, fitting into the grid diagram. The remaining problem is further 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 is maintained. The following techniques are applied for optimisation as explained in earlier papers, [5] a.o.:

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

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

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

Route 2 with a heater on cold stream C5 leads 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.

Evolution in route 3 leads to the same network as in route 1 with the heater on cold stream C2.

Both networks fully satisfy the energy targets. The network with the heater on cold stream C5 has the lowest cost (13317.88 k$/year); the difference with the other network, however, is marginal (680 $/year). The networks are shown in Figure 25.3 and in Figure 25.4. In both networks, heat exchanger unit A15 could be replaced by a second cooler, in which case the cost would go up with only 192 $/year.

Diverse 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 2.

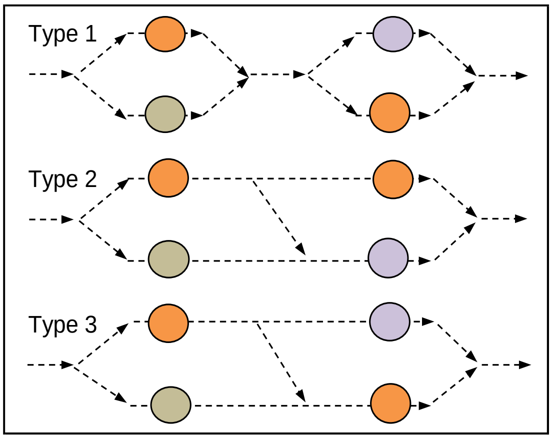

Figure 25.2

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

The annual costs of the best network with a heater on cold stream C5, respectively on C2 are compared with results from literature in Table 25.4. Threshold networks have not been reported in literature.

Table 25.4

	Heating	Cooling	Area	# units	# splits	Energy	Capital	Total cost	Heater
DTMin 10 K	kW	kW	m²	-	-	'000 $/y	'000 $/y	'000 $/y	on
Faria et al.	151.39	254.85	3 067	11	1	99 309.25	296.78	99 606.03	C5
Kim et al.	151.39	254.85	3 322	12	1	99 309.25	322.01	99 631.26	C5
Nair et al.	42.681	146.14	5 008	13	12	31 961.00	458.29	32 419.29	C4
This study									
Targets	11.91	115.37	4 138	15	-	12 896.50	401.27	13 297.77	
Results	11.91	115.37	4 263	17	10	12 896.50	421.38	13 317.88	C5
	11.91	115.37	4 269	17	10	12 896.50	422.07	13 318.56	C2
DTMin 9.0385 K									
Targets	0.00	103.46	4 369	14	-	5 519.49	413.92	5 933.41	-
Results	0.00	103.46	4 511	16	12	5 519.49	435.61	5 955.09	-

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 needed 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 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 those presented here.

Literature.

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[2] 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.

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

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

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DOI: 10.13140/RG.2.2.26429.51683

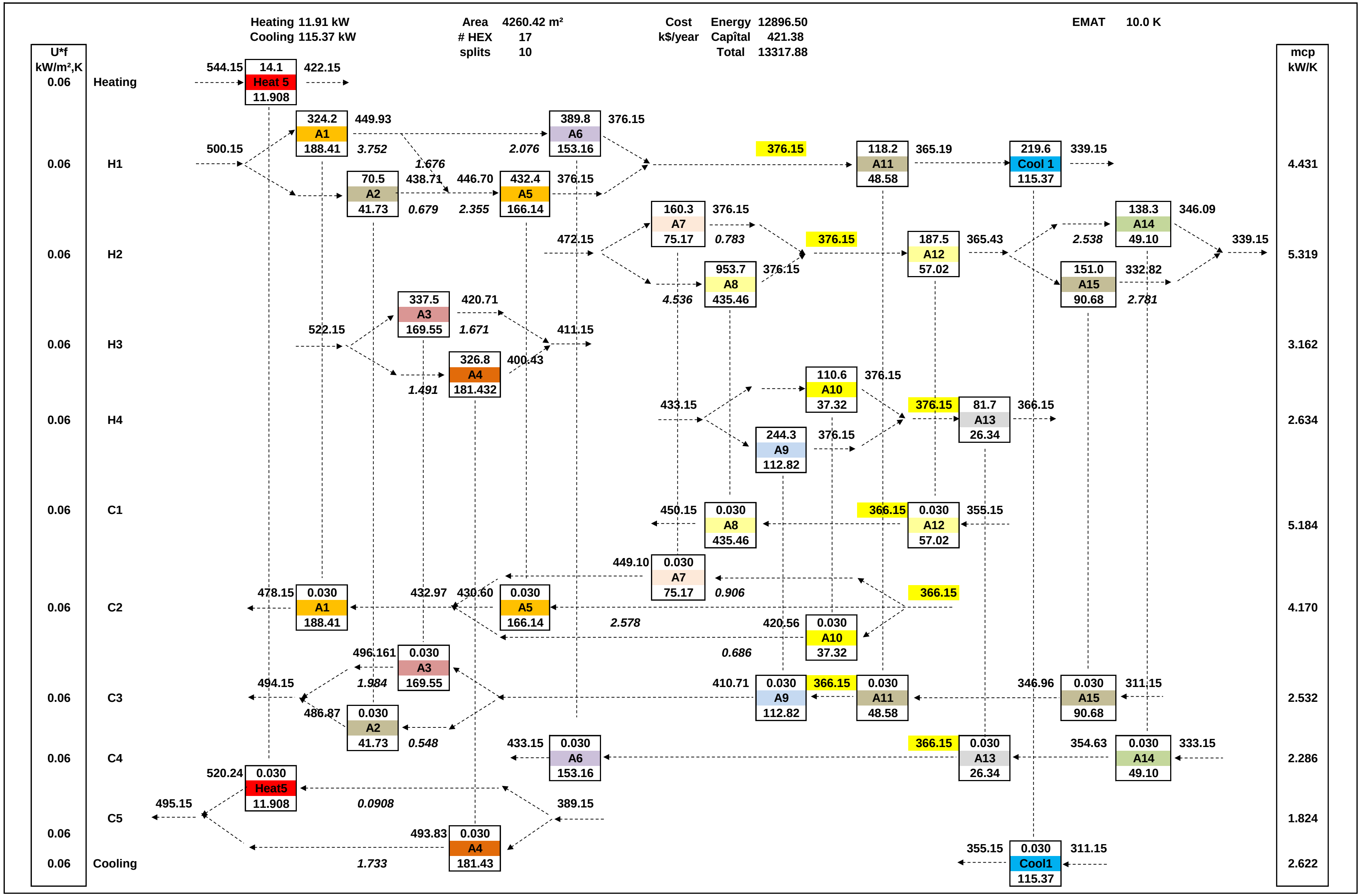
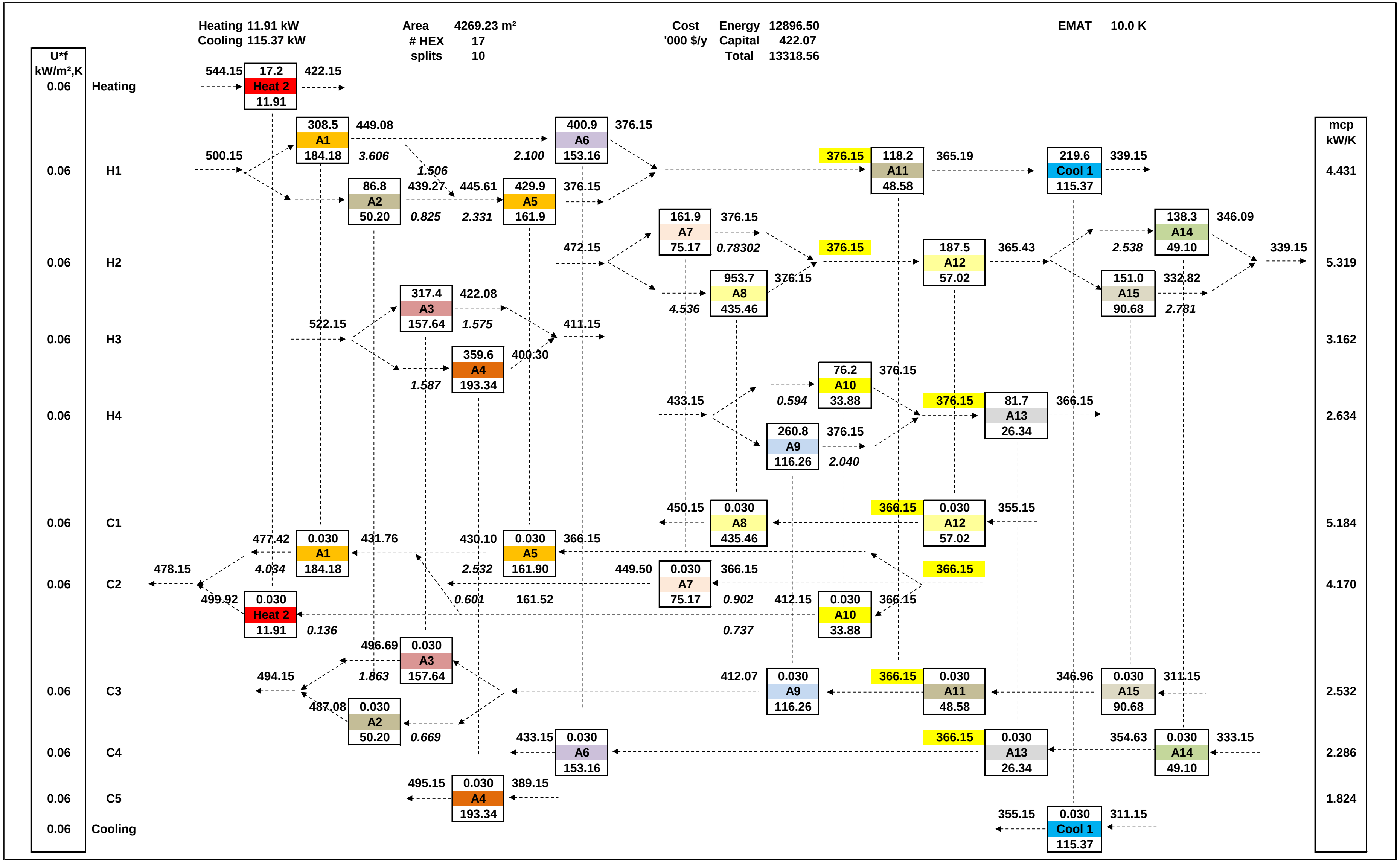

Heating 11.91 kW
Cooling 115.37 kW
Area 4260.42 m²
HEX 17
splits 10
Cost k$/year
Energy 12896.50
Capîtal 421.38
Total 13317.88
EMAT 10.0 K
U*f kW/m²,K
mcp kW/K
Heating
H1
H2
H3
H4
C1
C2
C3
C4
C5
Cooling
Heat 5
Heat5
A1
A2
A3
A4
A5
A6
A7
A8
A9
A10
A11
A12
A13
A14
A15
Cool 1
Cool1

Figure 25.3



Heating 11.91 kW
Cooling 115.37 kW
Area 4269.23 m²
HEX 17
splits 10
Cost '000 $/y
Energy 12896.50
Capital 422.07
Total 13318.56
EMAT 10.0 K
U*f kW/m²,K
0.06 Heating
0.06 H1
0.06 H2
0.06 H3
0.06 H4
0.06 C1
0.06 C2
0.06 C3
0.06 C4
0.06 C5
0.06 Cooling
mcp kW/K
4.431
5.319
3.162
2.634
5.184
4.170
2.532
2.286
1.824
544.15
17.2
Heat 2
11.91
422.15
500.15
308.5
A1
184.18
449.08
3.606
400.9
A6
153.16
376.15
2.100
1.506
86.8
A2
50.20
439.27
445.61
429.9
A5
161.9
376.15
0.825
2.331
376.15
118.2
A11
48.58
365.19
219.6
Cool 1
115.37
339.15
161.9
A7
75.17
376.15
0.78302
472.15
376.15
187.5
A12
57.02
365.43
138.3
A14
49.10
346.09
2.538
339.15
953.7
A8
435.46
376.15
4.536
151.0
A15
90.68
332.82
2.781
317.4
A3
157.64
422.08
1.575
522.15
411.15
359.6
A4
193.34
400.30
1.587
76.2
A10
33.88
376.15
433.15
0.594
376.15
81.7
A13
26.34
366.15
260.8
A9
116.26
376.15
2.040
450.15
0.030
A8
435.46
366.15
0.030
A12
57.02
355.15
477.42
0.030
A1
184.18
431.76
4.034
430.10
0.030
A5
161.90
366.15
2.532
478.15
449.50
0.030
A7
75.17
366.15
0.902
366.15
499.92
0.030
Heat 2
11.91
0.136
0.601
161.52
412.15
0.030
A10
33.88
366.15
0.737
496.69
0.030
A3
157.64
1.863
494.15
412.07
0.030
A9
116.26
366.15
0.030
A11
48.58
346.96
0.030
A15
90.68
311.15
487.08
0.030
A2
50.20
0.669
433.15
0.030
A6
153.16
366.15
0.030
A13
26.34
354.63
0.030
A14
49.10
333.15
495.15
0.030
A4
193.34
389.15
355.15
0.030
Cool 1
115.37
311.15

Figure 25.4

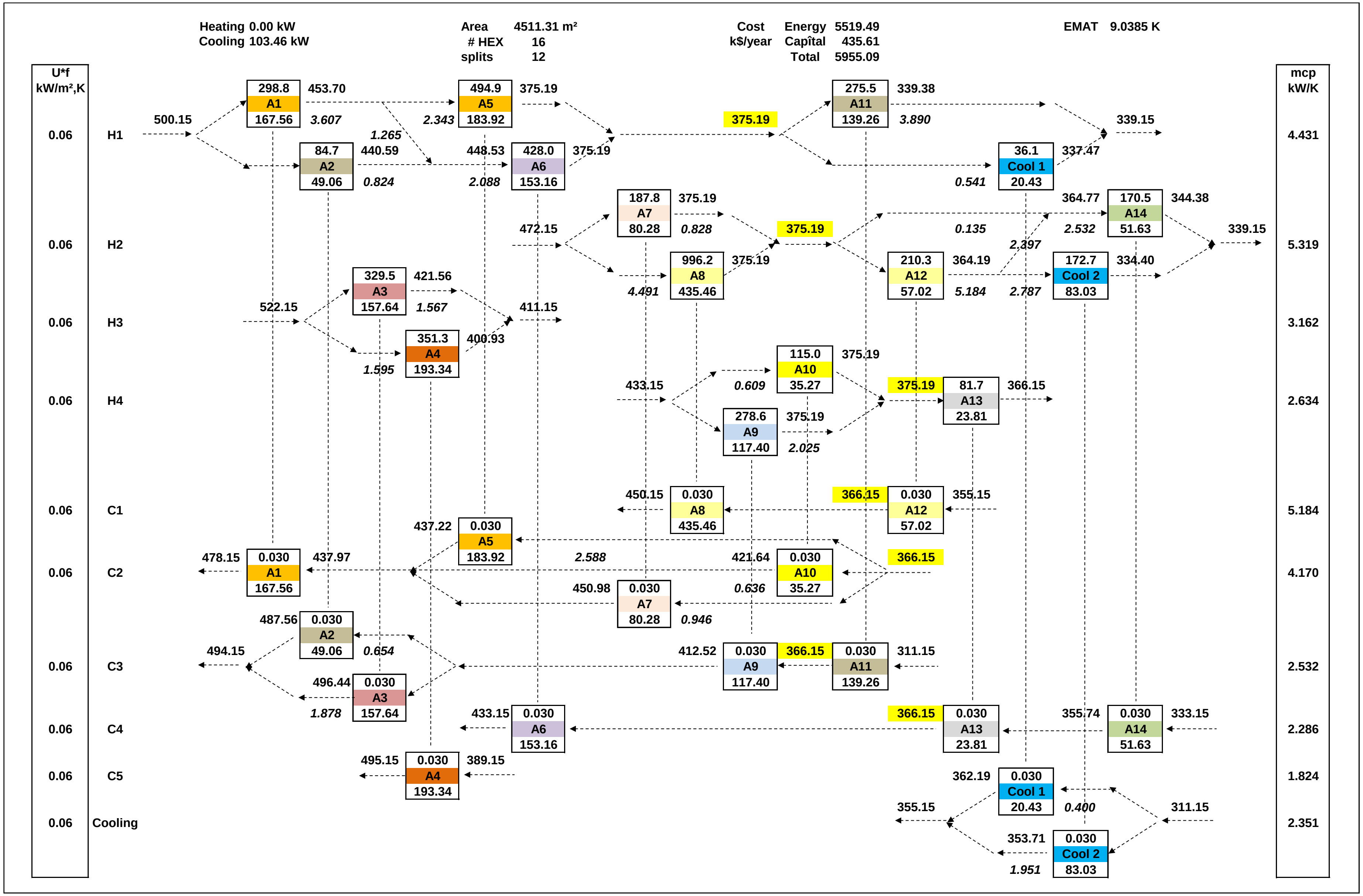

Heating 0.00 kW
Cooling 103.46 kW
Area 4511.31 m²
HEX 16
splits 12
Cost k$/year
Energy 5519.49
Capîtal 435.61
Total 5955.09
EMAT 9.0385 K
U*f kW/m²,K
mcp kW/K
H1
H2
H3
H4
C1
C2
C3
C4
C5
Cooling
0.06
4.431
5.319
3.162
2.634
5.184
4.170
2.532
2.286
1.824
2.351
500.15
298.8
A1
167.56
453.70
3.607
1.265
84.7
A2
49.06
440.59
0.824
494.9
A5
183.92
375.19
2.343
448.53
428.0
A6
153.16
2.088
375.19
275.5
A11
139.26
339.38
3.890
339.15
36.1
Cool 1
20.43
337.47
0.541
187.8
A7
80.28
375.19
0.828
472.15
996.2
A8
435.46
4.491
375.19
210.3
A12
57.02
364.19
5.184
0.135
364.77
170.5
A14
51.63
344.38
2.532
2.397
172.7
Cool 2
83.03
334.40
2.787
339.15
522.15
329.5
A3
157.64
421.56
1.567
411.15
351.3
A4
193.34
400.93
1.595
433.15
115.0
A10
35.27
375.19
0.609
278.6
A9
117.40
375.19
2.025
81.7
A13
23.81
366.15
450.15
0.030
355.15
437.22
2.588
478.15
437.97
421.64
0.636
450.98
0.946
487.56
494.15
0.654
496.44
1.878
412.52
311.15
433.15
355.74
333.15
495.15
389.15
362.19
0.400
311.15
355.15
353.71
1.951

Figure 25.5