Case 23 - Benchmark Solution for the Bandar Iman Aromatics Plant.

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Keywords: pinch analysis, heat exchanger network synthesis

The heat integration of the Bandar Imam Aromatics plant in the Persian Gulf, was first studied by Khorasany and Fesanghary [1]. It was an existing plant but was studied as a grass-root project with some simplifying assumptions. Stream data and financial parameters are presented in Table 23.1.

Table 23.1

Tsupply °C	Ttarget °C	Heat kW	Optim shift K	U*f kW/K,m²	Optim shift K	mcp kW/K
385	159	29 721.3	-26	1.238	H1	131.51
516	43	567 108.1	4	0.546	H2	1 198.96
132	82	18 926.0	0	0.771	H3	378.52
91	60	18 275.9	1	0.859	H4	589.55
217	43	32 401.6	2	1.000	H5	186.22
649	43	70 296.0	0	1.000	H6	116.00
30	385	42 280.5	-1	1.850	C1	119.10
99	471	71 070.6	3	1.129	C2	191.05
437	521	31 744.4	4	0.815	C3	377.91
78	419	54 642.5	8	1.000	C4	160.43
217	234	22 060.9	46	0.443	C5	1 297.70
256	266	27 530.0	-6	2.085	C6	2 753.00
49	149	19 739.0	0	1.000	C7	197.39
59	163	12 857.5	-1	1.063	C8	123.16
163	649	46 646.3	0	1.810	C9	95.98
219	221	4 594.3	1	1.377	C10	1 997.50
1800	800	8 700.0		1.200	Heating	
236	236	0.0		1.000	Steam	
38	82	412 262.9		1.000	Cooling	
	Flue gas	35.0	$/kW,year			
	Steam	27.0	$/kW,year			
	Cooling water	2.1	$/kW,year			
	Annual HEX cost = 26 600 + 4 147.5 x A $^{0.6}$					

Shift values have been optimised by crisscross optimization for minimum cost. Composite curves are shown in Figure 23.1. The pinch is caused by hot stream H2; the minimum number of units is 19 for a system segregated at the pinch (for one single system, the minimum number of units would be 17).

The trade-off curve is shown in Figure 23.2; the shape is very flat. The heating load has been chosen at 8700 kW flue gas, the minimum value of the trade-off curve. No steam is required. Increasing the heat load with 20% has no noticeable impact on the optimum shift values. Furthermore, the difference between vertical and criss-cross area is only 0.3%; the reason is the relatively small load on the process streams with high shift values.

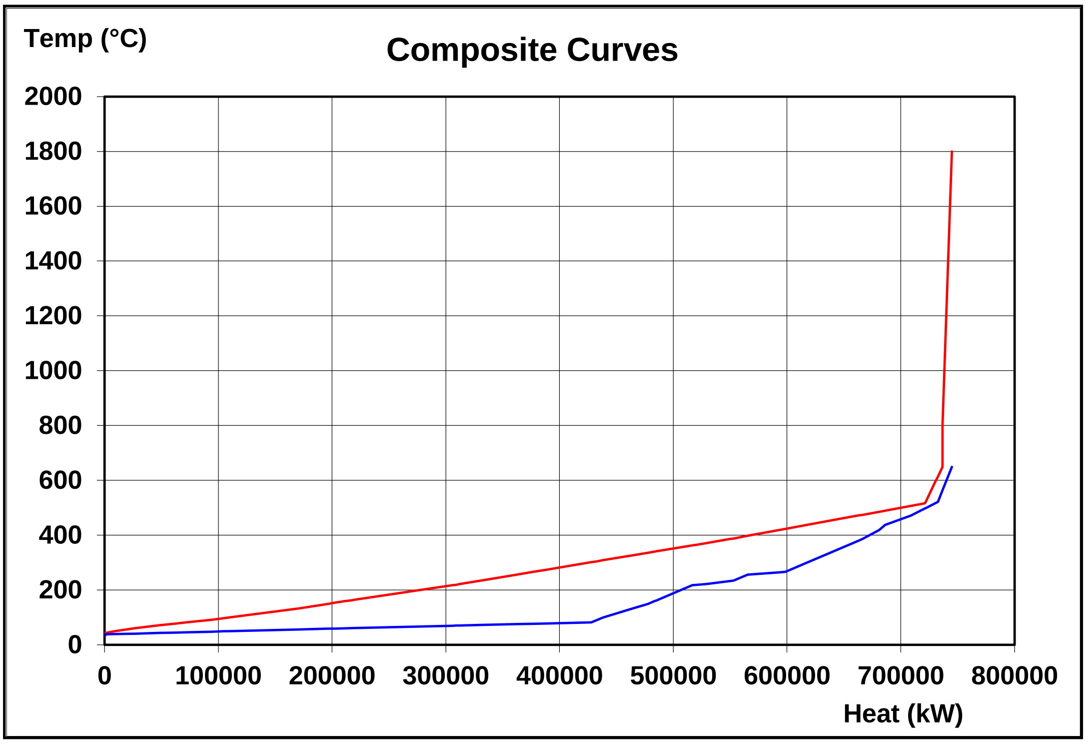

Figure 23.1

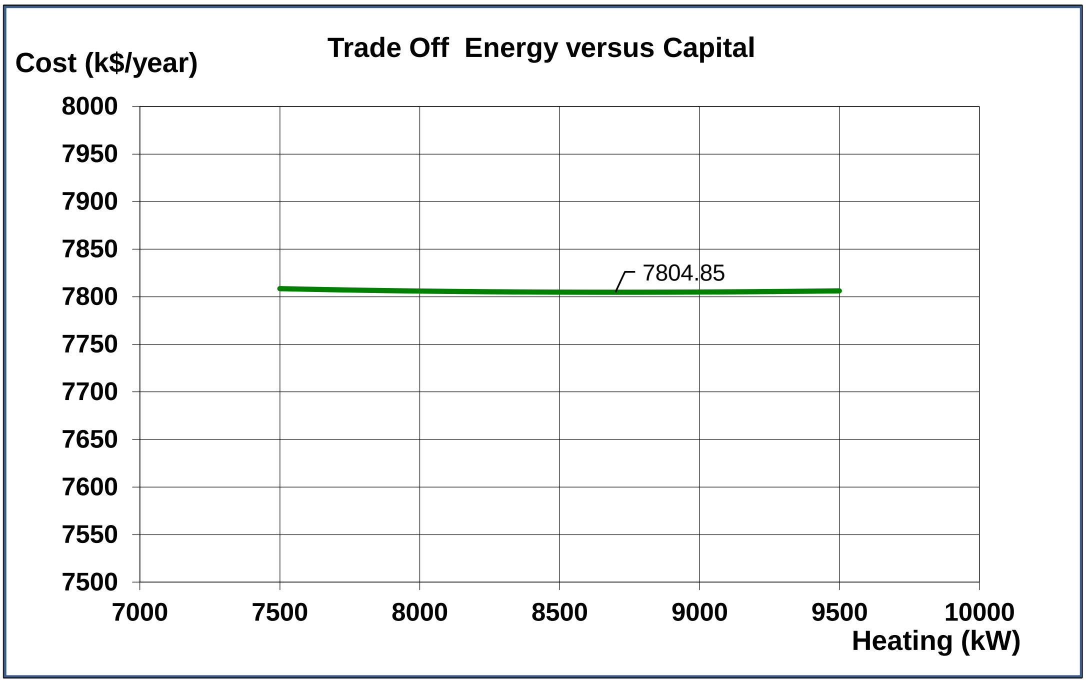

Figure 23.2

Pinch analysis for a heating load of 8700 kW generates data as shown in Table 23.2.
Investment cost is 85% of total cost. With the exponent of 0.6 in the cost formula, the actual area cost expectedly will be lower than the target, which is calculated with equal heat exchanger areas. The bigger the inequality of the real areas, the lower area cost can be expected.

Table 23.2

HEX area (vertical)	m²	28 414
HEX area (criss-cross)	m²	28 328
Cost Utilities	'000 $/year	1 170
Units	#	19
Cost Investment	'000 $/year	6 635
Total Cost	'000 $/year	7 805

The grid diagram contains 32 integration bands. Applying LP on the diagram generates a network with 153 heat exchanger units. Simplification of the grid seems appropriate. Further analysis indicates that the heat of hot streams H3, H4 and H5 is not needed for recovery to achieve the energy targets; their loads can be matched witch coolers.

In a first further procedure, the grid suggests the following matches:

- A heater on cold stream C9.
- Cold stream C2 fitting on a first branch of hot stream H2.

The target temperature of cold stream C3 can only be reached with hot stream H6. Due to mcp constraints, the load of the match must be limited; the remaining requirement of C3 can be taken from the second branch of H2. The remaining requirement of C9 after the heater can be taken from the rest of hot stream H6; the rest of hot stream H6 can go to a cooler.

The remaining grid diagram suggests matches between cold streams C1 and C4 with 2 sub-branches of the remaining second branch of H2. A third sub-branch is available for satisfying remaining loads. After these choices, an LP on the remaining problem offers a network that is suitable for final optimisation by fine-tuning the splits and, if appropriate, swaps of matches in the same integration band or even between adjacent bands to reduce total cost. The result is a network with eighteen units, three splits and a total cost of 6657.97 k$/year. It is shown in Figure 23.3.

In a second procedure, after reducing the number of integration bands on the high temperature side, heaters are suggested both on cold streams C3 and C9. The further allocation of matches is similar to that of the first procedure. The result is a network with eighteen units, three splits and a total cost of 6646.03 k$/year. It is shown in Figure 23.4.

Remarkably, the structure of both networks is almost. identical. Differences are:

- In the network with two heaters, the heater on cold stream C3 replaces the first heat exchanger on that stream with almost the same heat load.
- The total heating load with two heaters is 12.4% higher.
- The split distributions are only marginally different.

In a next step, the reduction of the number of splits is studied in case of one heater, respectively two heaters. The networks are shown in Figures 23.5 through 23.10. For the same number of splits, the networks with one and with two heaters are, again, remarkably similar. The matches, however, are different, depending on the number of splits. Although the networks with two splits have the lowest heating loads as well as the lowest areas, they do not have the lowest cost.

The average targeted heat exchanger area for a heating load of 9794 kW (the best design) is 1559 m². The average area in the best design is 1706 m²; the standard deviation of the areas is 3550 m², which indicates a very large inequality between the areas of the units; this explains why the area cost of the design is lower than the targeted area.

The results are summarised in Table 23.3. A comparison of the best network with three splits and with zero splits with publicly available results is given in Table 23.4.

Table 23.3

Heating	Area	Energy Cost	Capital Cost	Total	# HEX	# Splits
kW	m²	'000 $/year	'000 $/year	'000 $/year	-	-
1 Heater						
8717	30702	1170.88	5487.08	6657.97	18	3
8710	30578	1170.62	5496.00	6666.63	18	2
8759	30726	1172.44	5533.26	6705.70	18	1
8799	31063	1173.92	5665.67	6839.60	18	0
2 Heaters						
9794	30715	1210.84	5435.19	6646.03	18	3
9789	30589	1210.65	5444.04	6654.69	18	2
9846	30737	1212.77	5481.03	6693.80	18	1
9880	31076	1214.03	5613.68	6827.71	18	0

Table 23.4

Authors	Heating	Area	Total cost	# units	# splits
	MW	m²	'000 $/y		
Khorasany et al. (2009)	66.070	n.a.	7 435.74	18	2
Gorji-Bandpy et al. (2011)	77.550	n.a.	7 178.79	18	4
Huo et al. (2013) °)	38.799	27 983	7 238.96	17	4
Huo et al. (2013) °)	35.140	28 700	7 385.86	17	0
Pavão et al. (2017)	34.210	30 897	7 301.44	17	0
Zhang et al. (2017) °)	23.794	28 886	7 028.80	19	0
Aguitoni et al. (2018) °)	33.877	28 066	7 071.42	17	4
Zhang, Cui (2018)	10.630	31 397	6 861.11	18	0
Pavão et al. (2018)	9.498	31 012	6 712.55	18	5
Nair et al. (2019)	8.689	30 669	6 695.58	19	7
This work (2 heaters)	9.794	30 715	6 646.03	18	3
This work (2 heaters)	9.880	31 076	6 827.71	18	0
°) revised by the author					

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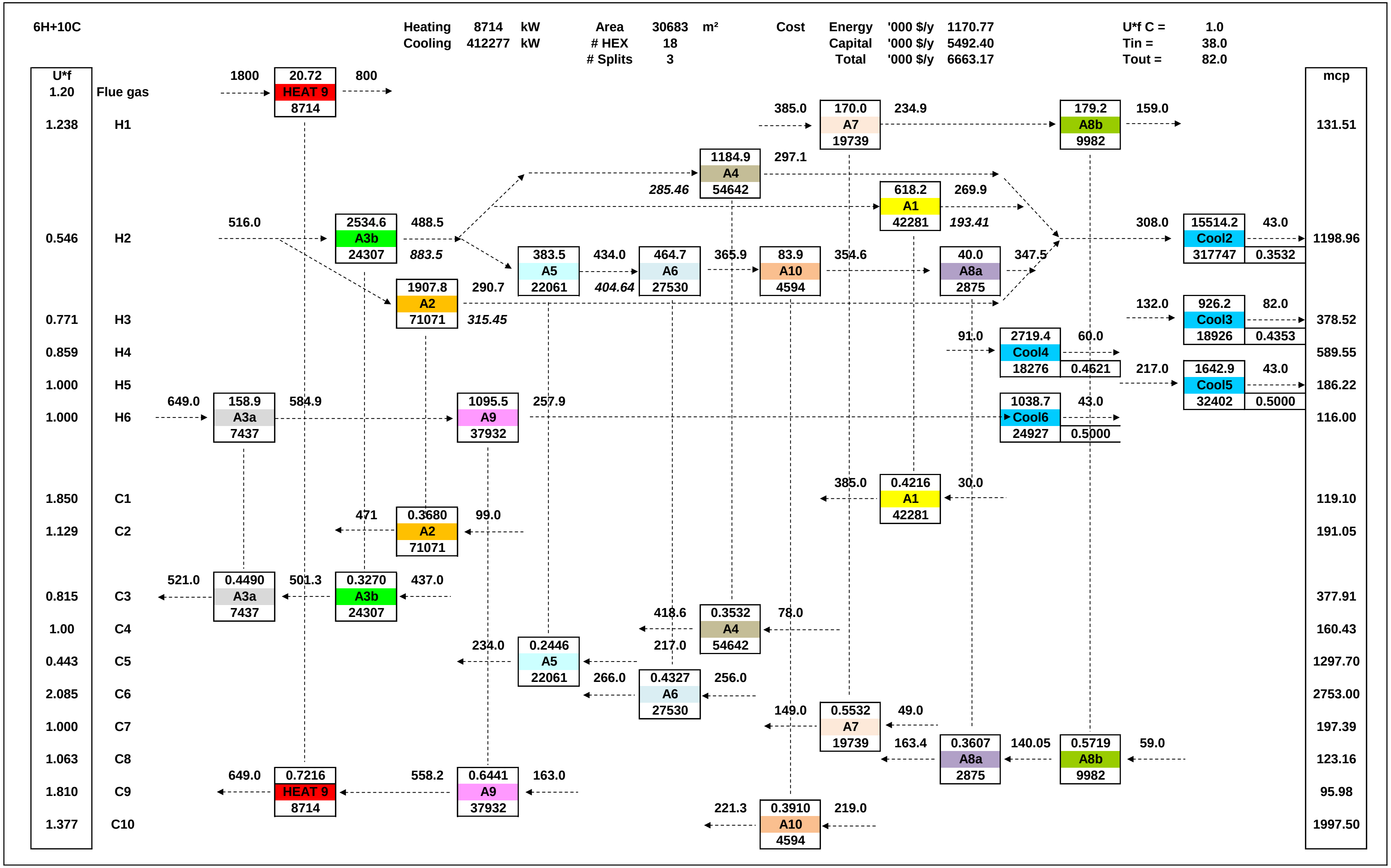
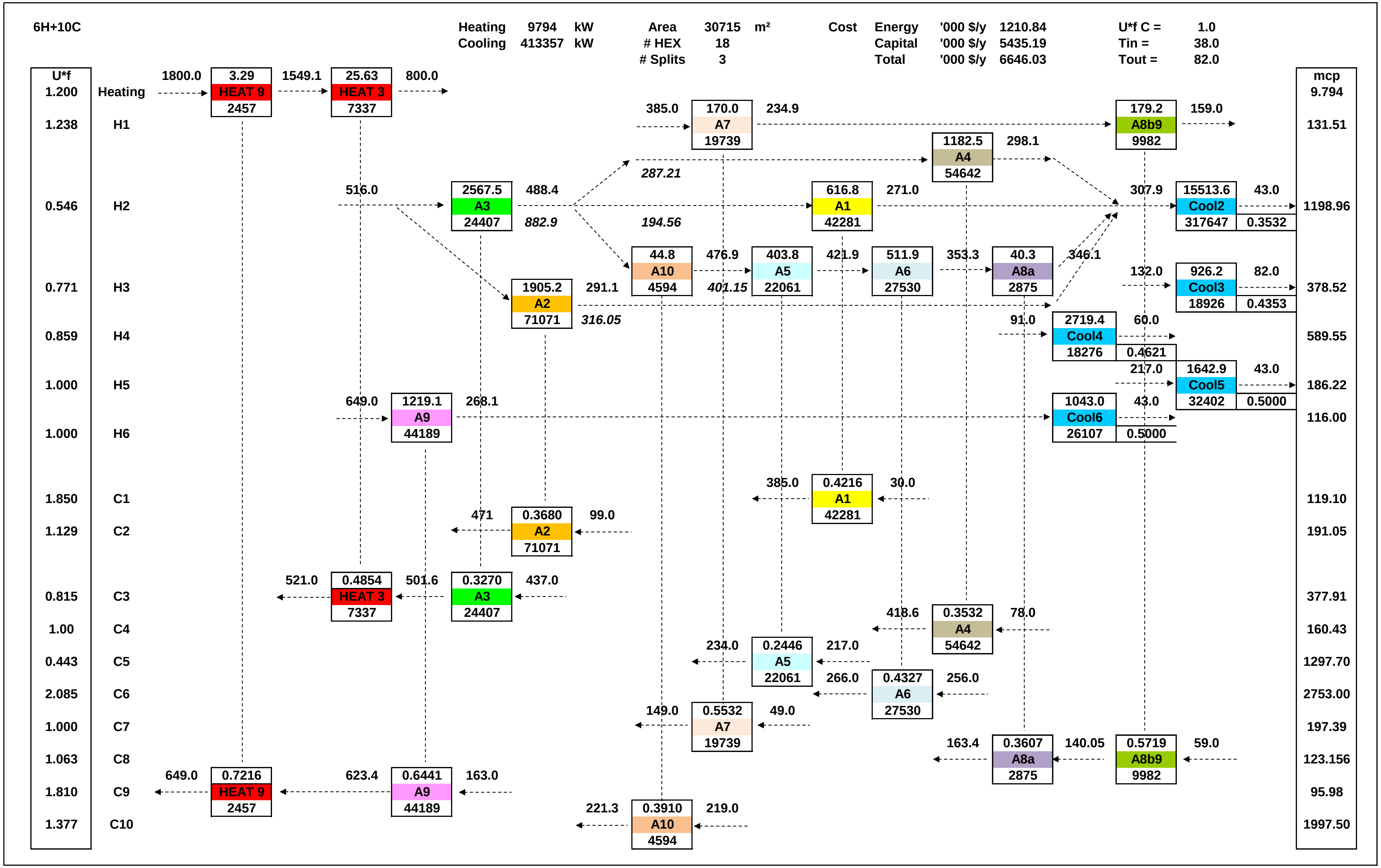

6H+10C
Heating 8714 kW
Cooling 412277 kW
Area 30683 m²
HEX 18
Splits 3
Cost
Energy '000 $/y 1170.77
Capital '000 $/y 5492.40
Total '000 $/y 6663.17
U*f C = 1.0
Tin = 38.0
Tout = 82.0
U*f
mcp
1.20 Flue gas
1800
20.72
HEAT 9
8714
800
1.238 H1
131.51
385.0
170.0
A7
19739
234.9
179.2
A8b
9982
159.0
1184.9
A4
54642
297.1
285.46
618.2
A1
42281
269.9
193.41
0.546 H2
1198.96
516.0
2534.6
A3b
24307
488.5
883.5
383.5
A5
22061
434.0
404.64
464.7
A6
27530
365.9
83.9
A10
4594
354.6
40.0
A8a
2875
347.5
308.0
15514.2
Cool2
317747
0.3532
43.0
1907.8
A2
71071
290.7
315.45
0.771 H3
378.52
132.0
926.2
Cool3
18926
0.4353
82.0
0.859 H4
589.55
91.0
2719.4
Cool4
18276
0.4621
60.0
1.000 H5
186.22
217.0
1642.9
Cool5
32402
0.5000
43.0
1.000 H6
116.00
649.0
158.9
A3a
7437
584.9
1095.5
A9
37932
257.9
1038.7
Cool6
24927
0.5000
43.0
1.850 C1
119.10
385.0
0.4216
A1
42281
30.0
1.129 C2
191.05
471
0.3680
A2
71071
99.0
0.815 C3
377.91
521.0
0.4490
A3a
7437
501.3
0.3270
A3b
24307
437.0
1.00 C4
160.43
418.6
0.3532
A4
54642
78.0
0.443 C5
1297.70
234.0
0.2446
A5
22061
217.0
2.085 C6
2753.00
266.0
0.4327
A6
27530
256.0
1.000 C7
197.39
149.0
0.5532
A7
19739
49.0
1.063 C8
123.16
163.4
0.3607
A8a
2875
140.05
0.5719
A8b
9982
59.0
1.810 C9
95.98
649.0
0.7216
HEAT 9
8714
558.2
0.6441
A9
37932
163.0
1.377 C10
1997.50
221.3
0.3910
A10
4594
219.0

Figure 23.3


6H+10C
Heating 9794 kW
Cooling 413357 kW
Area 30715 m²
HEX 18
Splits 3
Cost
Energy '000 $/y 1210.84
Capital '000 $/y 5435.19
Total '000 $/y 6646.03
U*f C = 1.0
Tin = 38.0
Tout = 82.0
U*f
1.200 Heating
1.238 H1
0.546 H2
0.771 H3
0.859 H4
1.000 H5
1.000 H6
1.850 C1
1.129 C2
0.815 C3
1.00 C4
0.443 C5
2.085 C6
1.000 C7
1.063 C8
1.810 C9
1.377 C10
mcp
9.794
131.51
1198.96
378.52
589.55
186.22
116.00
119.10
191.05
377.91
160.43
1297.70
2753.00
197.39
123.156
95.98
1997.50
1800.0
3.29 HEAT 9 2457
1549.1
25.63 HEAT 3 7337
800.0
385.0
170.0 A7 19739
234.9
179.2 A8b9 9982
159.0
1182.5 A4 54642
298.1
287.21
516.0
2567.5 A3 24407
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882.9
194.56
616.8 A1 42281
271.0
307.9
15513.6 Cool2 317647
43.0
0.3532
44.8 A10 4594
476.9
403.8 A5 22061
421.9
511.9 A6 27530
353.3
40.3 A8a 2875
346.1
132.0
926.2 Cool3 18926
82.0
0.4353
1905.2 A2 71071
291.1
401.15
316.05
91.0
2719.4 Cool4 18276
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1642.9 Cool5 32402
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268.1
1043.0 Cool6 26107
43.0
0.5000
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30.0
471
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521.0
0.4854 HEAT 3 7337
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78.0
234.0
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217.0
266.0
0.4327 A6 27530
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163.4
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140.05
0.5719 A8b9 9982
59.0
649.0
0.7216 HEAT 9 2457
623.4
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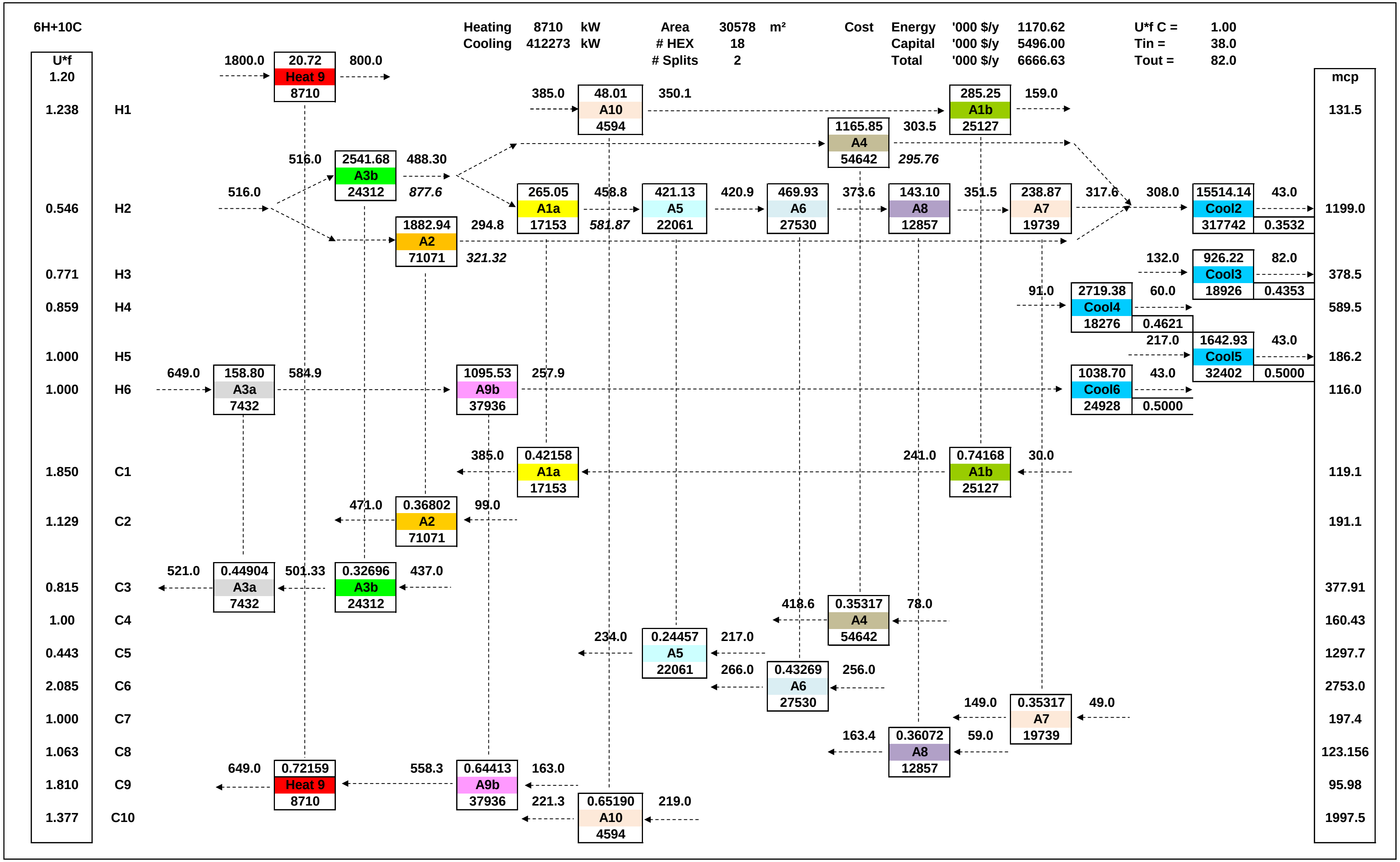
221.3
0.3910 A10 4594
219.0

Figure 23.4


6H+10C
Heating 8710 kW
Cooling 412273 kW
Area 30578 m²
HEX 18
Splits 2
Cost
Energy '000 $/y 1170.62
Capital '000 $/y 5496.00
Total '000 $/y 6666.63
U*f C = 1.00
Tin = 38.0
Tout = 82.0
U*f
1.20
mcp
1800.0
20.72
Heat 9
8710
800.0
1.238 H1 131.5
385.0
48.01
A10
4594
350.1
285.25
A1b
25127
159.0
1165.85
A4
54642
303.5
295.76
516.0
2541.68
A3b
24312
488.30
877.6
0.546 H2 1199.0
516.0
265.05
A1a
17153
458.8
581.87
421.13
A5
22061
420.9
469.93
A6
27530
373.6
143.10
A8
12857
351.5
238.87
A7
19739
317.6
308.0
15514.14
Cool2
317742
43.0
0.3532
1882.94
A2
71071
294.8
321.32
0.771 H3 378.5
132.0
926.22
Cool3
18926
82.0
0.4353
0.859 H4 589.5
91.0
2719.38
Cool4
18276
60.0
0.4621
1.000 H5 186.2
217.0
1642.93
Cool5
32402
43.0
0.5000
1.000 H6 116.0
649.0
158.80
A3a
7432
584.9
1095.53
A9b
37936
257.9
1038.70
Cool6
24928
43.0
0.5000
1.850 C1 119.1
385.0
0.42158
A1a
17153
241.0
0.74168
A1b
25127
30.0
1.129 C2 191.1
471.0
0.36802
A2
71071
99.0
0.815 C3 377.91
521.0
0.44904
A3a
7432
501.33
0.32696
A3b
24312
437.0
1.00 C4 160.43
418.6
0.35317
A4
54642
78.0
0.443 C5 1297.7
234.0
0.24457
A5
22061
217.0
2.085 C6 2753.0
266.0
0.43269
A6
27530
256.0
1.000 C7 197.4
149.0
0.35317
A7
19739
49.0
1.063 C8 123.156
163.4
0.36072
A8
12857
59.0
1.810 C9 95.98
649.0
0.72159
Heat 9
8710
558.3
0.64413
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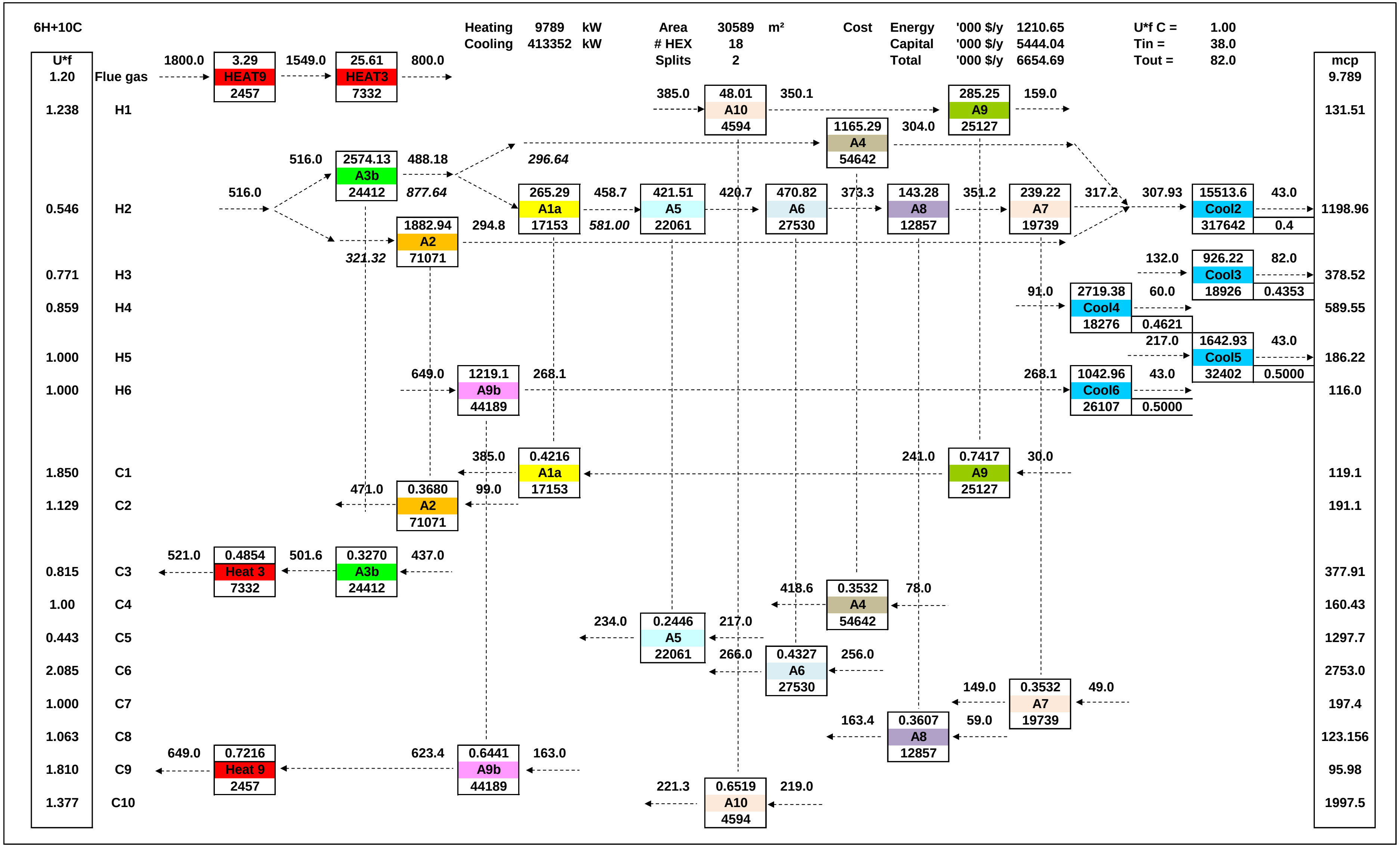
37936
163.0
1.377 C10 1997.5
221.3
0.65190
A10
4594
219.0

Figure 23.5


6H+10C
Heating 9789 kW
Cooling 413352 kW
Area 30589 m²
HEX 18
Splits 2
Cost
Energy '000 $/y 1210.65
Capital '000 $/y 5444.04
Total '000 $/y 6654.69
U*f C = 1.00
Tin = 38.0
Tout = 82.0
U*f
mcp
1.20
Flue gas
1800.0
3.29
HEAT9
2457
1549.0
25.61
HEAT3
7332
800.0
9.789
1.238
H1
385.0
48.01
A10
4594
350.1
285.25
A9
25127
159.0
131.51
1165.29
A4
54642
304.0
516.0
2574.13
A3b
24412
488.18
296.64
0.546
H2
516.0
877.64
265.29
A1a
17153
458.7
421.51
A5
22061
420.7
470.82
A6
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143.28
A8
12857
351.2
239.22
A7
19739
317.2
307.93
15513.6
Cool2
317642
43.0
0.4
1198.96
1882.94
A2
71071
294.8
581.00
321.32
132.0
926.22
Cool3
18926
82.0
0.4353
0.771
H3
378.52
91.0
2719.38
Cool4
18276
60.0
0.4621
0.859
H4
589.55
217.0
1642.93
Cool5
32402
43.0
0.5000
1.000
H5
186.22
649.0
1219.1
A9b
44189
268.1
268.1
1042.96
Cool6
26107
43.0
0.5000
1.000
H6
116.0
385.0
0.4216
A1a
17153
241.0
0.7417
A9
25127
30.0
1.850
C1
119.1
471.0
0.3680
A2
71071
99.0
1.129
C2
191.1
521.0
0.4854
Heat 3
7332
501.6
0.3270
A3b
24412
437.0
0.815
C3
377.91
418.6
0.3532
A4
54642
78.0
1.00
C4
160.43
234.0
0.2446
A5
22061
217.0
0.443
C5
1297.7
266.0
0.4327
A6
27530
256.0
2.085
C6
2753.0
149.0
0.3532
A7
19739
49.0
1.000
C7
197.4
163.4
0.3607
A8
12857
59.0
1.063
C8
123.156
649.0
0.7216
Heat 9
2457
623.4
0.6441
A9b
44189
163.0
1.810
C9
95.98
221.3
0.6519
A10
4594
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C10
1997.5

Figure 23.6

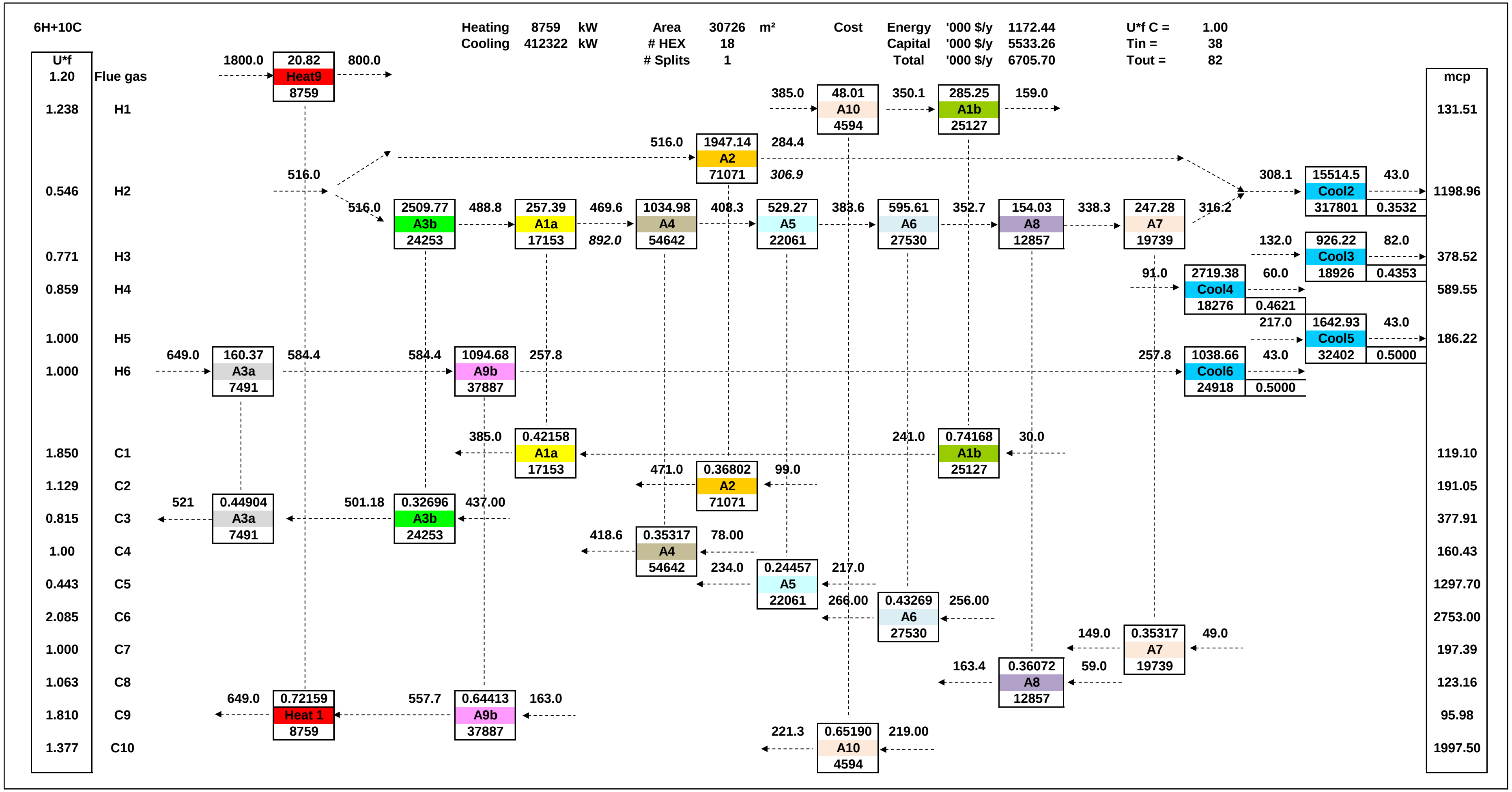
6H+10C
Heating 8759 kW
Cooling 412322 kW
Area 30726 m²
HEX 18
Splits 1
Cost
Energy '000 $/y 1172.44
Capital '000 $/y 5533.26
Total '000 $/y 6705.70
U*f C = 1.00
Tin = 38
Tout = 82
U*f
1.20
Flue gas
1.238 H1
0.546 H2
0.771 H3
0.859 H4
1.000 H5
1.000 H6
1.850 C1
1.129 C2
0.815 C3
1.00 C4
0.443 C5
2.085 C6
1.000 C7
1.063 C8
1.810 C9
1.377 C10
mcp
131.51
1198.96
378.52
589.55
186.22
119.10
191.05
377.91
160.43
1297.70
2753.00
197.39
123.16
95.98
1997.50
1800.0
20.82
Heat9
8759
800.0
385.0
48.01
A10
4594
350.1
285.25
A1b
25127
159.0
516.0
1947.14
A2
71071
284.4
306.9
516.0
308.1
15514.5
Cool2
317801
43.0
0.3532
516.0
2509.77
A3b
24253
488.8
257.39
A1a
17153
469.6
892.0
1034.98
A4
54642
408.3
529.27
A5
22061
383.6
595.61
A6
27530
352.7
154.03
A8
12857
338.3
247.28
A7
19739
316.2
132.0
926.22
Cool3
18926
82.0
0.4353
91.0
2719.38
Cool4
18276
60.0
0.4621
217.0
1642.93
Cool5
32402
43.0
0.5000
649.0
160.37
A3a
7491
584.4
584.4
1094.68
A9b
37887
257.8
257.8
1038.66
Cool6
24918
43.0
0.5000
385.0
0.42158
A1a
17153
241.0
0.74168
A1b
25127
30.0
471.0
0.36802
A2
71071
99.0
521
0.44904
A3a
7491
501.18
0.32696
A3b
24253
437.00
418.6
0.35317
A4
54642
78.00
234.0
0.24457
A5
22061
217.0
266.00
0.43269
A6
27530
256.00
149.0
0.35317
A7
19739
49.0
163.4
0.36072
A8
12857
59.0
649.0
0.72159
Heat 1
8759
557.7
0.64413
A9b
37887
163.0
221.3
0.65190
A10
4594
219.00

Figure 23.7

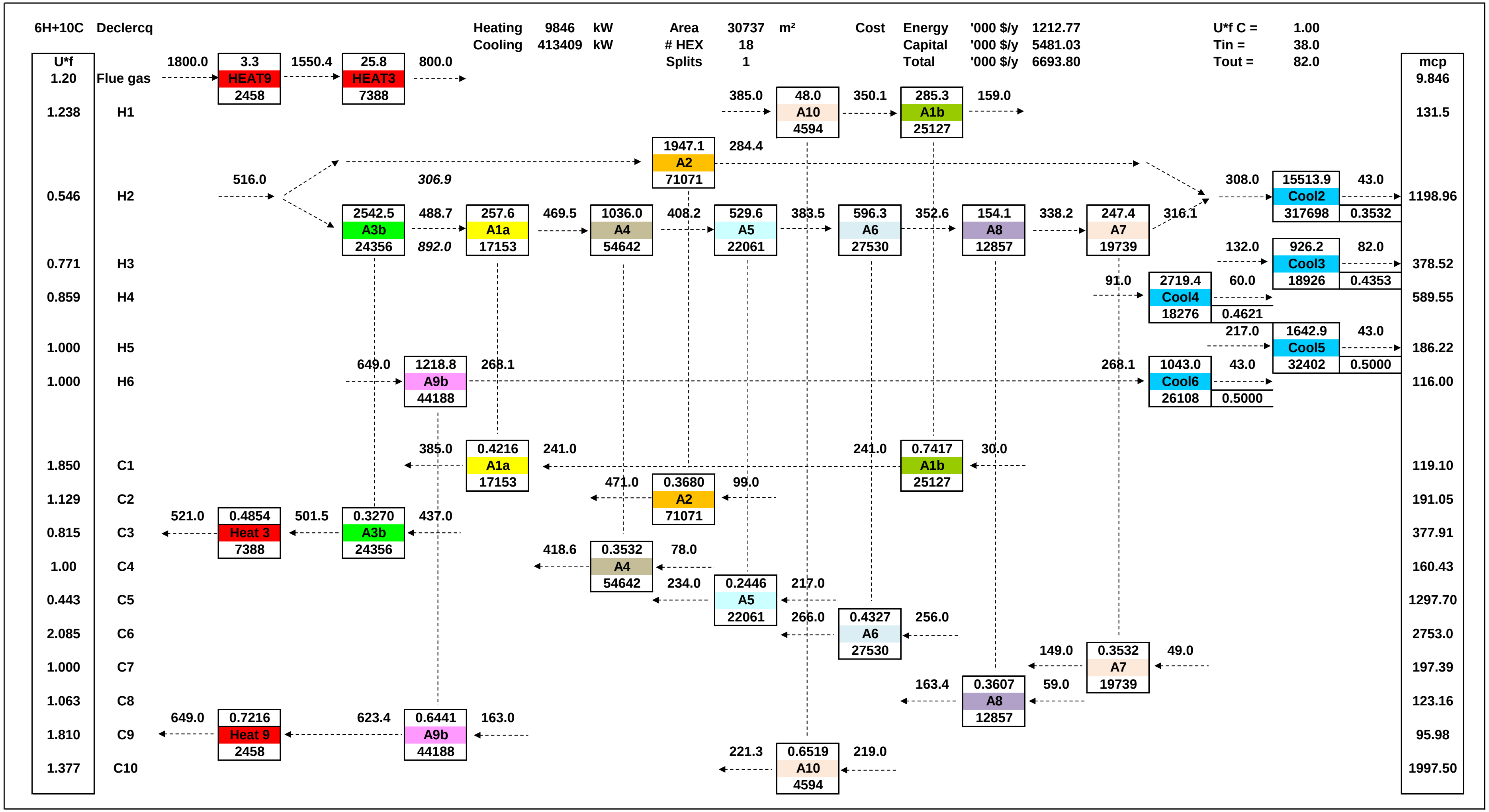
6H+10C Declercq
Heating 9846 kW
Cooling 413409 kW
Area 30737 m²
HEX 18
Splits 1
Cost
Energy '000 $/y 1212.77
Capital '000 $/y 5481.03
Total '000 $/y 6693.80
U*f C = 1.00
Tin = 38.0
Tout = 82.0
U*f
1.20 Flue gas
1.238 H1
0.546 H2
0.771 H3
0.859 H4
1.000 H5
1.000 H6
1.850 C1
1.129 C2
0.815 C3
1.00 C4
0.443 C5
2.085 C6
1.000 C7
1.063 C8
1.810 C9
1.377 C10
mcp
9.846
131.5
1198.96
378.52
589.55
186.22
116.00
119.10
191.05
377.91
160.43
1297.70
2753.0
197.39
123.16
95.98
1997.50
1800.0
3.3 HEAT9 2458
1550.4
25.8 HEAT3 7388
800.0
385.0
48.0 A10 4594
350.1
285.3 A1b 25127
159.0
1947.1 A2 71071
284.4
516.0
306.9
892.0
2542.5 A3b 24356
488.7
257.6 A1a 17153
469.5
1036.0 A4 54642
408.2
529.6 A5 22061
383.5
596.3 A6 27530
352.6
154.1 A8 12857
338.2
247.4 A7 19739
316.1
308.0
15513.9 Cool2 317698
43.0
0.3532
132.0
926.2 Cool3 18926
82.0
0.4353
91.0
2719.4 Cool4 18276
60.0
0.4621
217.0
1642.9 Cool5 32402
43.0
0.5000
649.0
1218.8 A9b 44188
268.1
268.1
1043.0 Cool6 26108
43.0
0.5000
385.0
0.4216 A1a 17153
241.0
241.0
0.7417 A1b 25127
30.0
471.0
0.3680 A2 71071
99.0
521.0
0.4854 Heat 3 7388
501.5
0.3270 A3b 24356
437.0
418.6
0.3532 A4 54642
78.0
234.0
0.2446 A5 22061
217.0
266.0
0.4327 A6 27530
256.0
149.0
0.3532 A7 19739
49.0
163.4
0.3607 A8 12857
59.0
649.0
0.7216 Heat 9 2458
623.4
0.6441 A9b 44188
163.0
221.3
0.6519 A10 4594
219.0

Figure 23.8

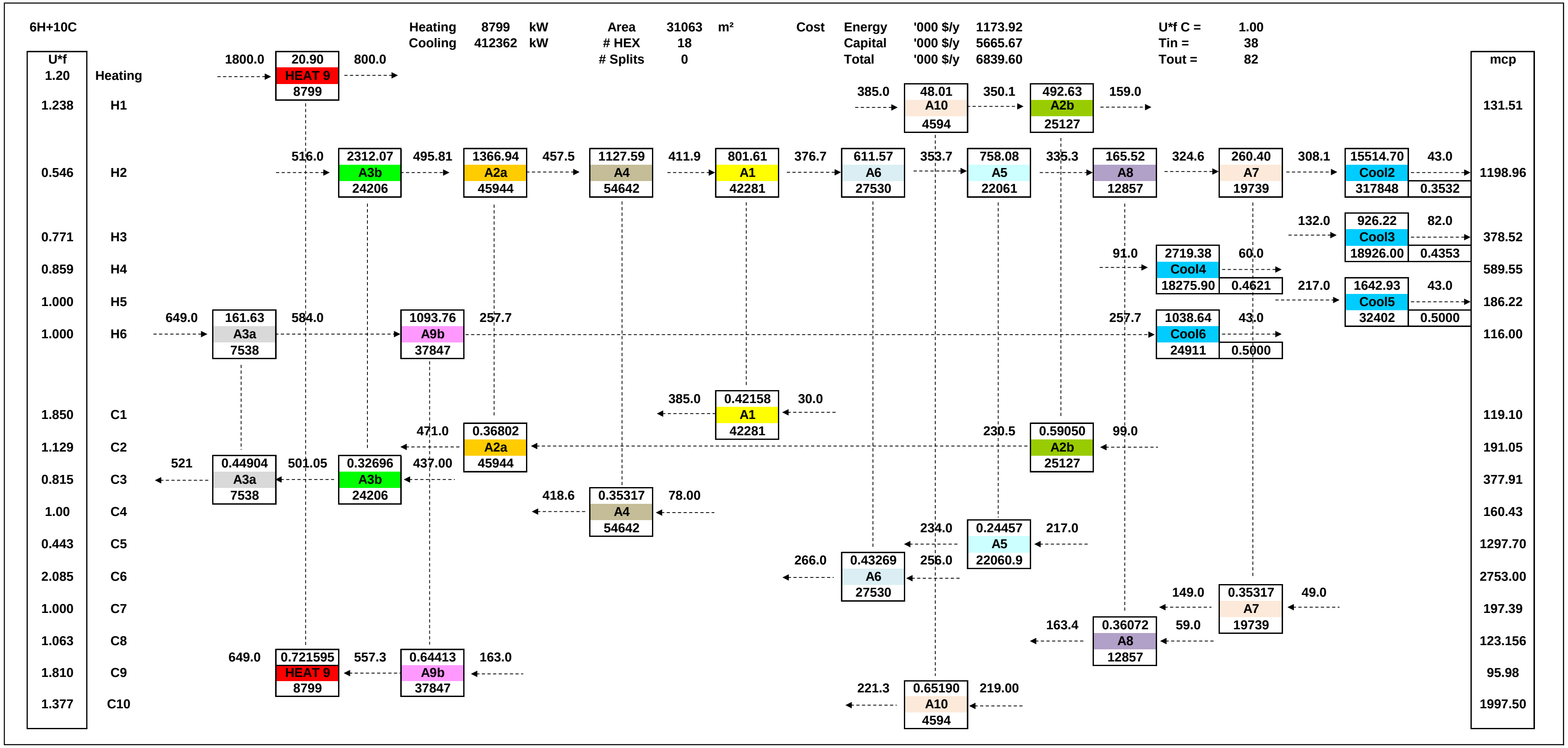
6H+10C
Heating 8799 kW
Cooling 412362 kW
Area 31063 m²
HEX 18
Splits 0
Cost
Energy '000 $/y 1173.92
Capital '000 $/y 5665.67
Total '000 $/y 6839.60
U*f C = 1.00
Tin = 38
Tout = 82
U*f
1.20 Heating
1800.0
20.90
HEAT 9
8799
800.0
mcp
1.238 H1
385.0
48.01
A10
4594
350.1
492.63
A2b
25127
159.0
131.51
0.546 H2
516.0
2312.07
A3b
24206
495.81
1366.94
A2a
45944
457.5
1127.59
A4
54642
411.9
801.61
A1
42281
376.7
611.57
A6
27530
353.7
758.08
A5
22061
335.3
165.52
A8
12857
324.6
260.40
A7
19739
308.1
15514.70
Cool2
317848
0.3532
43.0
1198.96
0.771 H3
132.0
926.22
Cool3
18926.00
0.4353
82.0
378.52
0.859 H4
91.0
2719.38
Cool4
18275.90
0.4621
60.0
589.55
1.000 H5
217.0
1642.93
Cool5
32402
0.5000
43.0
186.22
1.000 H6
649.0
161.63
A3a
7538
584.0
1093.76
A9b
37847
257.7
257.7
1038.64
Cool6
24911
0.5000
43.0
116.00
1.850 C1
385.0
0.42158
A1
42281
30.0
119.10
1.129 C2
471.0
0.36802
A2a
45944
230.5
0.59050
A2b
25127
99.0
191.05
0.815 C3
521
0.44904
A3a
7538
501.05
0.32696
A3b
24206
437.00
377.91
1.00 C4
418.6
0.35317
A4
54642
78.00
160.43
0.443 C5
234.0
0.24457
A5
22060.9
217.0
1297.70
2.085 C6
266.0
0.43269
A6
27530
256.0
2753.00
1.000 C7
149.0
0.35317
A7
19739
49.0
197.39
1.063 C8
163.4
0.36072
A8
12857
59.0
123.156
1.810 C9
649.0
0.721595
HEAT 9
8799
557.3
0.64413
A9b
37847
163.0
95.98
1.377 C10
221.3
0.65190
A10
4594
219.00
1997.50

Figure 23.9

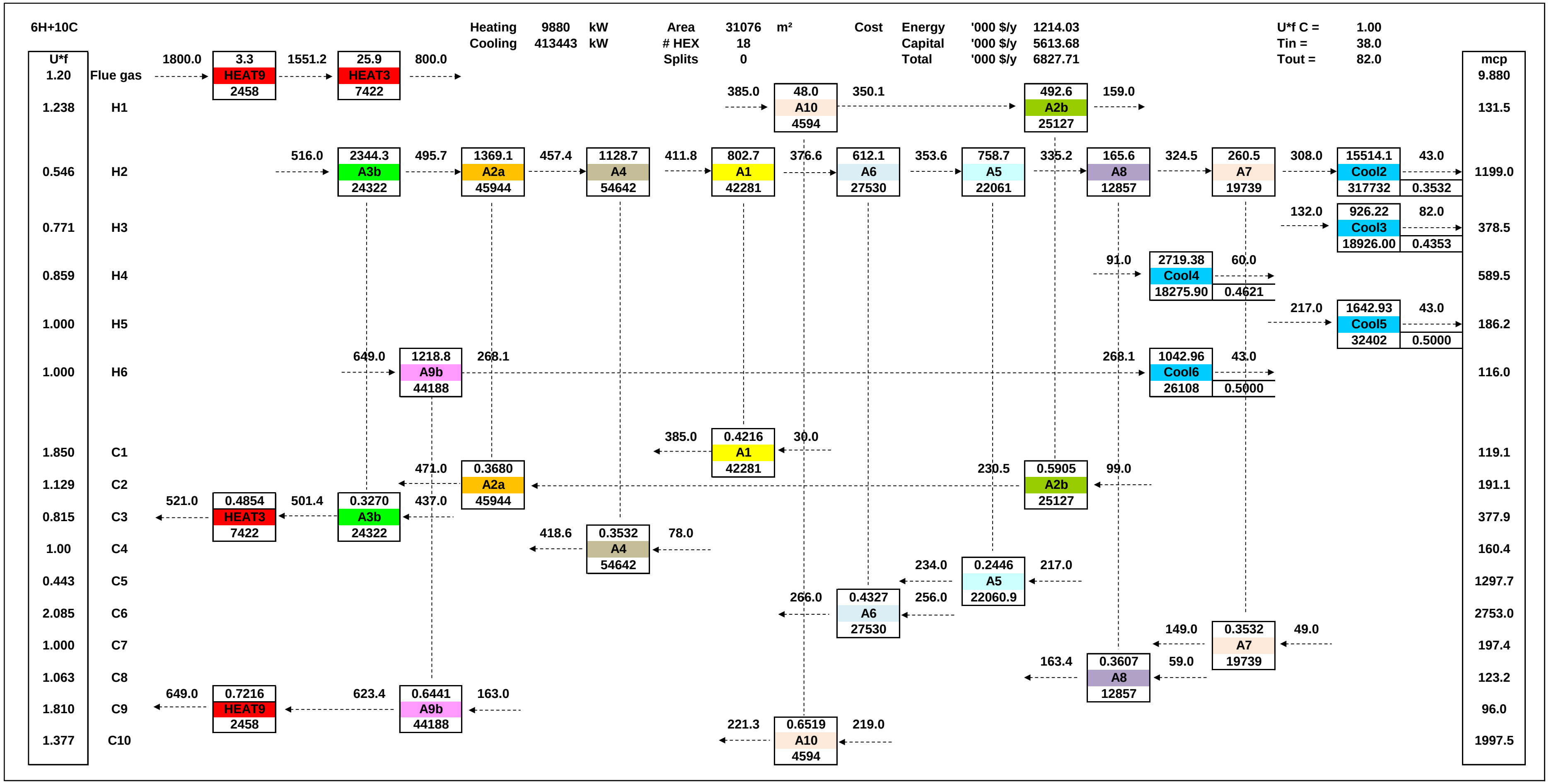
6H+10C
Heating 9880 kW
Cooling 413443 kW
Area 31076 m²
HEX 18
Splits 0
Cost
Energy '000 $/y 1214.03
Capital '000 $/y 5613.68
Total '000 $/y 6827.71
U*f C = 1.00
Tin = 38.0
Tout = 82.0
U*f
mcp
1.20 Flue gas 9.880
1.238 H1 131.5
0.546 H2 1199.0
0.771 H3 378.5
0.859 H4 589.5
1.000 H5 186.2
1.000 H6 116.0
1.850 C1 119.1
1.129 C2 191.1
0.815 C3 377.9
1.00 C4 160.4
0.443 C5 1297.7
2.085 C6 2753.0
1.000 C7 197.4
1.063 C8 123.2
1.810 C9 96.0
1.377 C10 1997.5
1800.0
3.3 HEAT9 2458
1551.2
25.9 HEAT3 7422
800.0
385.0
48.0 A10 4594
350.1
492.6 A2b 25127
159.0
516.0
2344.3 A3b 24322
495.7
1369.1 A2a 45944
457.4
1128.7 A4 54642
411.8
802.7 A1 42281
376.6
612.1 A6 27530
353.6
758.7 A5 22061
335.2
165.6 A8 12857
324.5
260.5 A7 19739
308.0
15514.1 Cool2 317732 0.3532
43.0
132.0
926.22 Cool3 18926.00 0.4353
82.0
91.0
2719.38 Cool4 18275.90 0.4621
60.0
217.0
1642.93 Cool5 32402 0.5000
43.0
649.0
1218.8 A9b 44188
268.1
268.1
1042.96 Cool6 26108 0.5000
43.0
385.0
0.4216 A1 42281
30.0
471.0
0.3680 A2a 45944
230.5
0.5905 A2b 25127
99.0
521.0
0.4854 HEAT3 7422
501.4
0.3270 A3b 24322
437.0
418.6
0.3532 A4 54642
78.0
234.0
0.2446 A5 22060.9
217.0
266.0
0.4327 A6 27530
256.0
149.0
0.3532 A7 19739
49.0
163.4
0.3607 A8 12857
59.0
649.0
0.7216 HEAT9 2458
623.4
0.6441 A9b 44188
163.0
221.3
0.6519 A10 4594
219.0

Figure 23.10