The importance of driving forces in heat exchanger network design

Case 16 - The Example from Björk and Pettersson revisited

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This 15 streams problem has already been studied in **Case 5 ï Example from Björk and Pettersson** and reported on the Pinchco website**.** The data are given in Table 16.1. The shift values have been optimised for the given heating load. The impact of the differences in heat transfer coefficients, however, is moderate; with vertical heat exchange, the area target is 3867 m², with optimised crisscross it is 3749 m² (-3%).

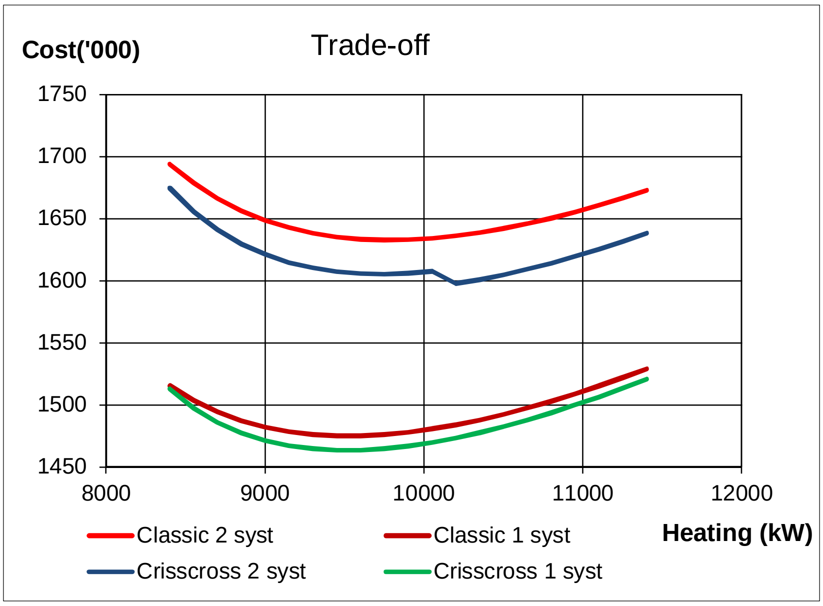
Table 16.1

T supply °C	T target °C	Heat kW	Shift K	U*f kW/m²/K	Description -
180	75	3150	0.0	2.0	H1
280	120	9600	3.0	1.0	H2
180	75	3150	0.0	2.0	H3
140	40	3000	3.0	1.0	H4
220	120	5000	3.0	1.0	H5
180	55	4375	0.0	2.0	H6
200	60	4200	9.0	0.4	H7
120	40	8000	7.0	0.5	H8
40	230	3800	3.0	1.0	C1
100	220	7200	3.0	1.0	C2
40	190	5250	0.0	2.0	C3
50	190	4200	0.0	2.0	C4
50	250	12000	0.0	2.0	C5
90	190	5000	3.0	1.0	C6
160	250	5400	-2.0	3.0	C7
325.1	325	9800	0.0	1.0	Heating
25	40	7425		2.0	Cooling
Heating 80/kW ; Cooling 10/kW Annual HEX cost = 8000 + 500 x $A^{0.75}$					

The data set is characterised by a high number of potential matches between heat loads and heat capacity flow rates, offering the possibility of multiple independent systems in view of reducing the number of heat exchanger units. However, having more independent systems will reduce overall heat integration and the flexibility to respond to changing energy prices. Moreover, such networks are seldom operable in reality in view of start up and variations of process conditions. Consequently, this data set is of academic interest in the first place, rather than for industrial practice but, nevertheless, solving the case is a challenge for pinch technologists as well as for mathematical programming specialists.

The trade-off curves for a pinched configuration (with a heat exchanger network above the pinch and a network below the pinch) and for one independent system are shown in Figure16.1. The step changes in the curves are caused by a change in the number of units and strict application of vertical heat exchange in the grid diagrams. The classic pinch analysis with a pinched system requires 27 units; the pinch is caused by hot stream H4. With crisscross optimisation, the pinched system requires only 26 units for a heating load below 10 000 kW (this explains half of the difference in cost compared with the classic analysis) and 25 units above 10200 kW; there are 2 pinches, the first being caused by hot stream H8, the second by cold stream C2. In the case of one single system, the minimum number of units is 16.

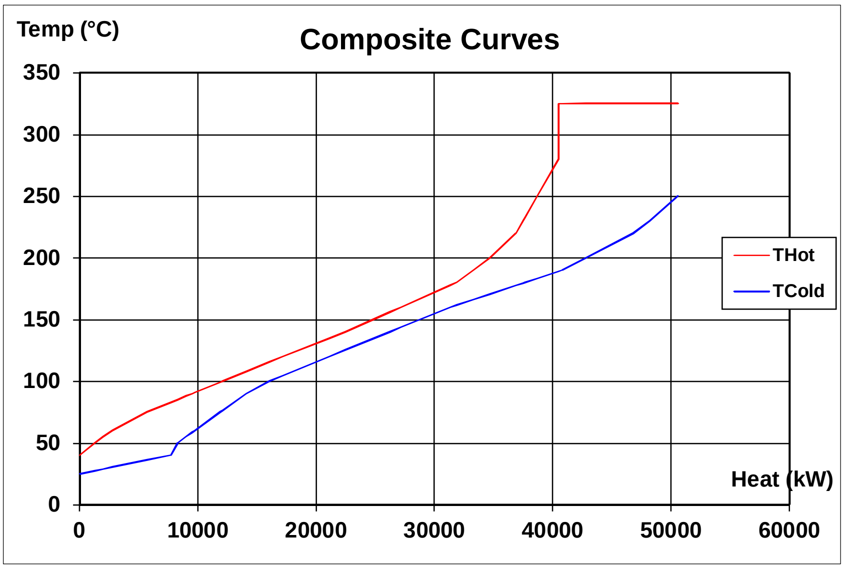
Figure 16.1



Experience has shown that optimum networks tend to have a number of units that is close to the minimum and, as such, expectedly, networks should be feasible for an annual cost below 1500K, with a heating load below 10 000 kW and a number of units that does not far exceed 16. An initial heating load of 9800 kW has been be chosen, although a value of 9500 kW would lead to the same results.

The composite curves, shown in Figure 16.2, are parallel over a wide range.

Figure 16.2



With the specifics of the data set, the designer may be attracted to creating independent systems in order to reduce the minimum number of units but, by doing so, may give away too much driving force. In this update, particular attention will be paid to the use of available driving forces.

The following steps are applied:

- Development of the grid diagram for the data set in Table 16.1, however with uniform shift values such that results are verifiable with standard pinch analysis tools
- Inspection of heat loads and heat capacity flowrates in order to identify potential matches covering the range where the composite curves are parallel
- Comparison of the available driving force at the pinch with the driving force used in a match
- Analysis of the remaining problem, the remaining driving force and the total cost if a suggested match were accepted
- Once a set of matches is accepted, development of the new grid diagram in order to solve the remaining problem.

Potential matches can be identified in the parallel section of the CC’s as shown in Table 16.2.:

Table 16.2

		Units	Cost ('000) Classic		DeltaT at pinch (K)
	Base case	16	1476.58		13.53
1	Match H1/H3 - C5 middle	2	75.59		13.53
	remaining problem	15	1413.28		13.53
	Total	17	1488.87		
	Delta		12.29	0.83%	
2	Match H6 - cold end C3	1	43.29		15.00
	remaining problem	15	1433.50		13.30
	Total	16	1476.79		
	Delta		0.21	0.01%	
3	Match H7 - C4	1	113.74		10.00
	remaining problem	14	1366.44		14.00
	Total	15	1480.18		
	Delta		3.60	0.24%	
4	Match cold end H2 - C2	1	77.50		20.00
	remaining problem	15	1409.37		11.54
	Total	16	1486.87		
	Delta		10.29	0.70%	
5	Match H5 - C6	1	47.00		30.00
	remaining problem	14	1445.03		9.51
	Total	15	1492.03		
	Delta		15.45	1.05%	
	Matches 1, 2 & 3	4	232.62		
	remaining problem	12	1259.64		13.95
	Total	16	1492.26		
	Delta		15.68	1.06%	

Matches 1, 2 and 3 would seem to be acceptable; if implemented, then the minimum driving force left for the remaining problem is 13.95K and the cost target would increase with only 1.06%.

Match 4 is questionable since a lot of driving force is given away, reducing the driving force for the remaining problem by 15% from 13.53K to 11.54K. After acceptance of the previous matches 1, 2 and 3, that minimum driving force would even be reduced by 37% from 13.95K to 8.76K. On the other hand, a match between sections of H2 and C2 would be appropriate to cover the parallel section of the composite curves and, so, a match 4b could be established with a DeltaT equal to the average minimum driving force of 13.95K between the cold end of H2 and the hot end of C2. It also appears that, if such match is not established at this stage, it will automatically emerge when solving the remaining problem in order to satisfy mcp requirements at the pinch.

Match 5 is questionable for the same reason: too much driving force is given away; also here, it seems appropriate to establish a match 5b between sections of H5 and C6 with a DeltaT of 13.95K.

The results of implementing matches 4b and 5b are shown in Table 16.3.

Table 16.3

		Units	Cost ('000) Classic		DeltaT at pinch (K)
	New Base case	16	1492.26		13.95
	Matches 1, 2 & 3	4	232.62		
4b	Match cold end H2 - hot end C2	1	95.59		13.95
	remaining problem	12	1186.31		13.95
	Total	17	1514.52		
	Delta		22.26	1.49%	
	Matches 1, 2 & 3	4	232.62		
5b	Match cold end H5 - hot end C6	1	68.78		13.95
	remaining problem	12	1205.93		13.95
	Total	17	1507.33		
	Delta		15.07	1.01%	

Once the above matches are configured, the remaining problem can be solved.

Below the pinch, following the tick-off procedure, there is only one single solution as shown in the initial network in Figure 16.5.

Above the pinch, the remaining problem contains 3 hot streams (the remaining hot sections of H2 and of H5 and the hot utility) and 4 cold streams (C7 and the hot sections of C1, C3 and C5). In view of the possible combinations, the number of configurations to be investigated would be (4!*3!)/2 = 72. Further, if a remaining hot stream contains 2 matches, also the sequence of these matches could be relevant; if a remaining cold stream contains 2 matches with hot process streams, also then the sequence could be relevant. Therefore, a large number of potential matches needs to be studied; the procedure to be used, however, is not arbitrary, but is straightforward and can be structured in a very systematic way.

An overview of the results of the study is shown in Figure 16.3.

Series 1 refers to 45 networks developed after accepting matches 1, 2, 3, 4b and 5b. Match 4b, initiated with the mentioned DeltaT of 13.95 K, ends up in all cases with a DeltaT of 20 K after evolution which would be equivalent with accepting match 4 instead of 4b from the start. In total, 45 networks could be developed with a cost below 1503 K. The most promising initial network of Figure 16.4 can be developed into a network with 16 units and a cost of 1492.66 K as shown in Figure16.6.

The 45 networks are within a cost range of 0.7%; 8 networks have 16 units, 37 networks have 17 units.

Series 2 refers to 19 networks as developed in Series 1, however with match 3 refined following the same procedure as applied for match 5b. The best network for this configuration has a cost of 1493.57 K and is shown in Figure 16.7.

The 19 networks are within a cost range of 1.1%; 1 network has17 units, 6 networks have 18 units, 12 networks have 19 units.Other networks may exist within the given range. The further refinement of match 3 leads to higher heating loads and more units, the cost of which cannot be over-compensated by lower areas (Figure 16.4). The choice of match 3 was therefore correct.

When accepting match 5 instead of 5b, the best network has a cost of 1510.59 K; match 5b appears to be mandatory for achieving the optimum configuration.

Without considering the utilities, the matches 1, 2, 3, 4 and 5b with 6 exchangers take 87% of the area for 79% of the integration and constitute the core of a series of networks with a cost of 1500 K +/- 0.5%; said matches are essential, the remaining 10 or 11 exchangers are for fine-tuning.

Only networks with 1 stream split have been considered.

This example illustrates that it is possible to develop optimum networks in a sequential procedure, starting with an in-depth analysis in order to define a reasonable utility load, study of the character of the composite curves and developing the network step by step, taking into account the specificities of the process streams. It also demonstrates the importance of not giving away driving force.

The HEN problem is very rational and does not answer the rules of Darwin's evolution theory.

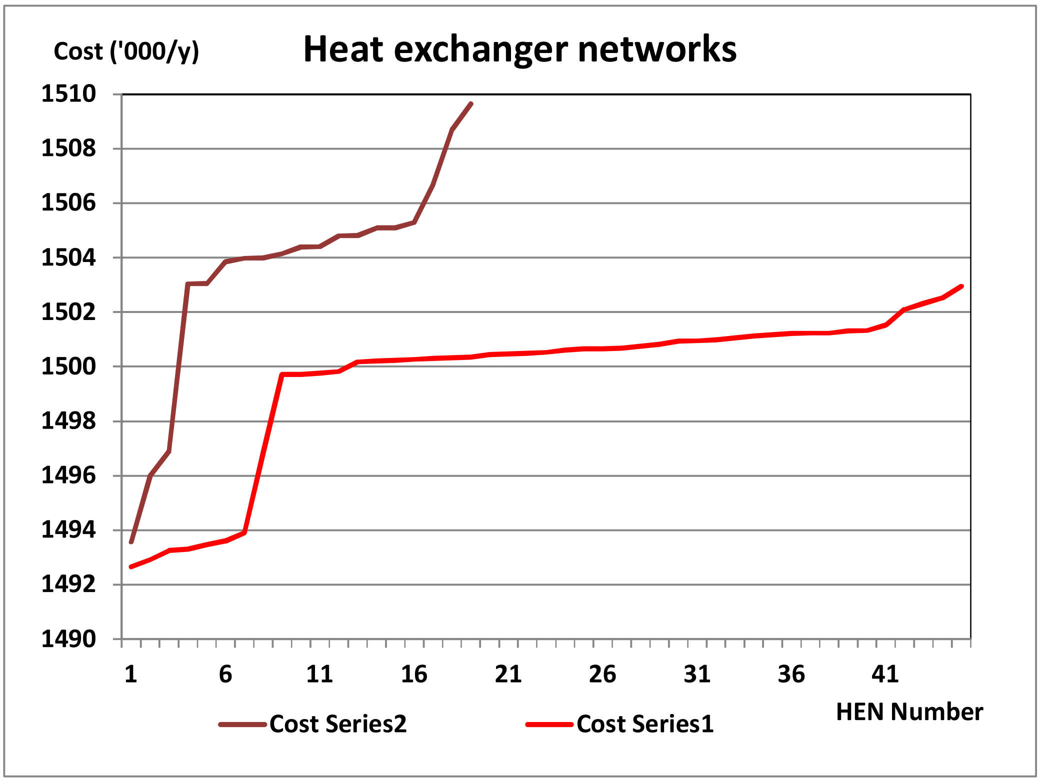


Figure 16.3

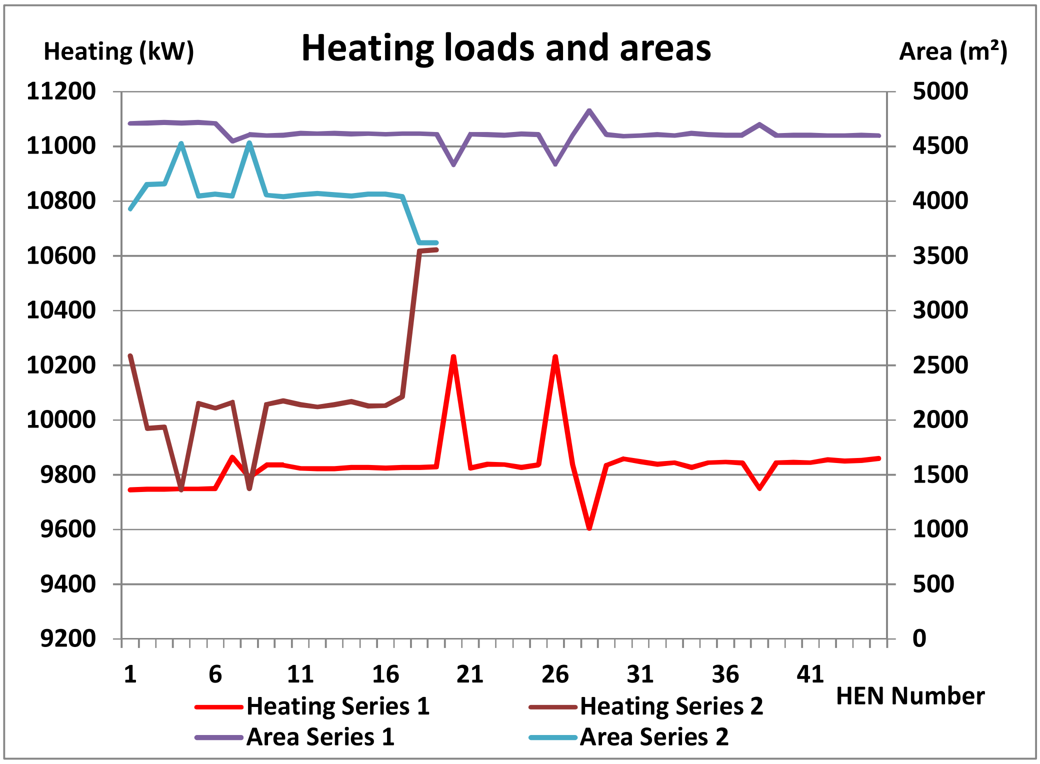


Figure 16.4

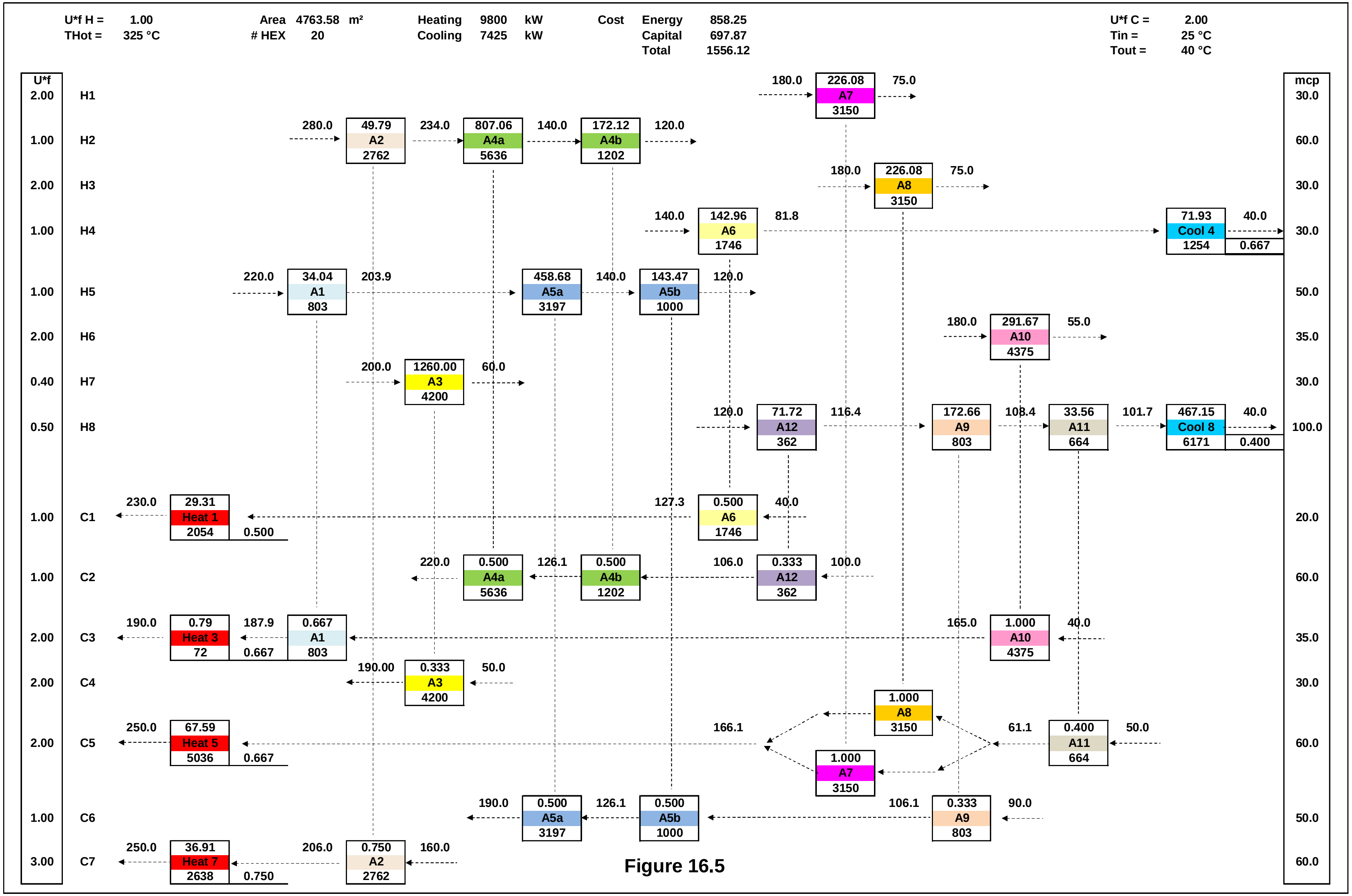

U*f H = 1.00
THot = 325 °C
Area 4763.58 m²
HEX 20
Heating 9800 kW
Cooling 7425 kW
Cost
Energy 858.25
Capital 697.87
Total 1556.12
U*f C = 2.00
Tin = 25 °C
Tout = 40 °C
U*f
mcp
2.00 H1 30.0
1.00 H2 60.0
2.00 H3 30.0
1.00 H4 30.0
1.00 H5 50.0
2.00 H6 35.0
0.40 H7 30.0
0.50 H8 100.0
1.00 C1 20.0
1.00 C2 60.0
2.00 C3 35.0
2.00 C4 30.0
2.00 C5 60.0
1.00 C6 50.0
3.00 C7 60.0
180.0
226.08
A7
3150
75.0
280.0
49.79
A2
2762
234.0
807.06
A4a
5636
140.0
172.12
A4b
1202
120.0
180.0
226.08
A8
3150
75.0
140.0
142.96
A6
1746
81.8
71.93
Cool 4
1254
40.0
0.667
220.0
34.04
A1
803
203.9
458.68
A5a
3197
140.0
143.47
A5b
1000
120.0
180.0
291.67
A10
4375
55.0
200.0
1260.00
A3
4200
60.0
120.0
71.72
A12
362
116.4
172.66
A9
803
108.4
33.56
A11
664
101.7
467.15
Cool 8
6171
40.0
0.400
230.0
29.31
Heat 1
2054
0.500
127.3
0.500
A6
1746
40.0
220.0
0.500
A4a
5636
126.1
0.500
A4b
1202
106.0
0.333
A12
362
100.0
190.0
0.79
Heat 3
72
0.667
187.9
0.667
A1
803
165.0
1.000
A10
4375
40.0
190.00
0.333
A3
4200
50.0
1.000
A8
3150
250.0
67.59
Heat 5
5036
0.667
166.1
61.1
0.400
A11
664
50.0
1.000
A7
3150
190.0
0.500
A5a
3197
126.1
0.500
A5b
1000
106.1
0.333
A9
803
90.0
250.0
36.91
Heat 7
2638
0.750
206.0
0.750
A2
2762
160.0

Figure 16.5

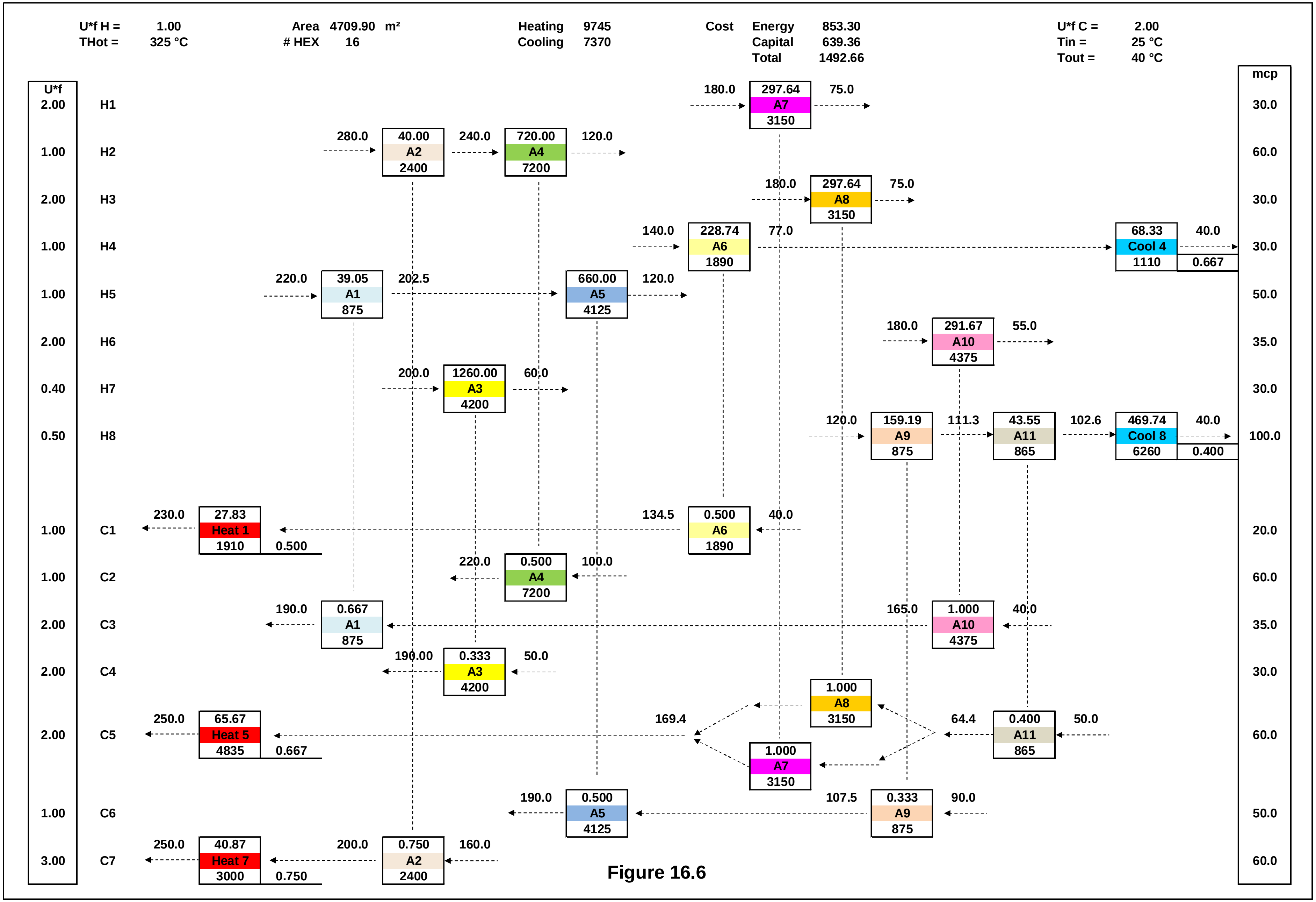

U*f H = 1.00
THot = 325 °C
Area 4709.90 m²
HEX 16
Heating 9745
Cooling 7370
Cost
Energy 853.30
Capital 639.36
Total 1492.66
U*f C = 2.00
Tin = 25 °C
Tout = 40 °C
U*f
mcp
2.00 H1 30.0
1.00 H2 60.0
2.00 H3 30.0
1.00 H4 30.0
1.00 H5 50.0
2.00 H6 35.0
0.40 H7 30.0
0.50 H8 100.0
1.00 C1 20.0
1.00 C2 60.0
2.00 C3 35.0
2.00 C4 30.0
2.00 C5 60.0
1.00 C6 50.0
3.00 C7 60.0
180.0
297.64
A7
3150
75.0
280.0
40.00
A2
2400
240.0
720.00
A4
7200
120.0
180.0
297.64
A8
3150
75.0
140.0
228.74
A6
1890
77.0
68.33
Cool 4
1110
40.0
0.667
220.0
39.05
A1
875
202.5
660.00
A5
4125
120.0
180.0
291.67
A10
4375
55.0
200.0
1260.00
A3
4200
60.0
120.0
159.19
A9
875
111.3
43.55
A11
865
102.6
469.74
Cool 8
6260
40.0
0.400
230.0
27.83
Heat 1
1910
0.500
134.5
0.500
A6
1890
40.0
220.0
0.500
A4
7200
100.0
190.0
0.667
A1
875
165.0
1.000
A10
4375
40.0
190.00
0.333
A3
4200
50.0
1.000
A8
3150
250.0
65.67
Heat 5
4835
0.667
169.4
64.4
0.400
A11
865
50.0
1.000
A7
3150
190.0
0.500
A5
4125
107.5
0.333
A9
875
90.0
250.0
40.87
Heat 7
3000
0.750
200.0
0.750
A2
2400
160.0

Figure 16.6

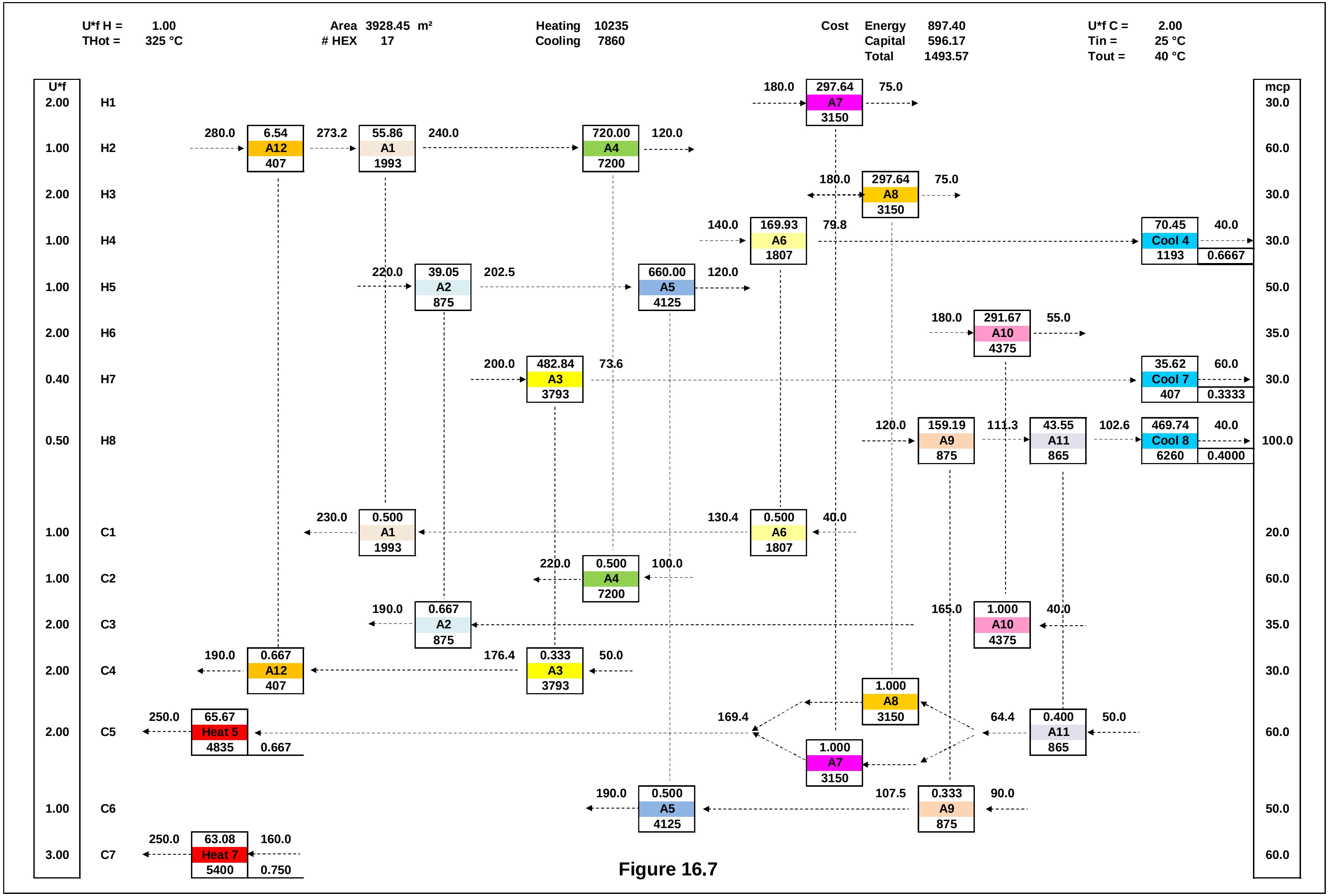

U*f H = 1.00
THot = 325 °C
Area 3928.45 m²
HEX 17
Heating 10235
Cooling 7860
Cost
Energy 897.40
Capital 596.17
Total 1493.57
U*f C = 2.00
Tin = 25 °C
Tout = 40 °C
U*f
mcp
2.00 H1 30.0
1.00 H2 60.0
2.00 H3 30.0
1.00 H4 30.0
1.00 H5 50.0
2.00 H6 35.0
0.40 H7 30.0
0.50 H8 100.0
1.00 C1 20.0
1.00 C2 60.0
2.00 C3 35.0
2.00 C4 30.0
2.00 C5 60.0
1.00 C6 50.0
3.00 C7 60.0
180.0 297.64 A7 3150 75.0
280.0 6.54 A12 407 273.2 55.86 A1 1993 240.0 720.00 A4 7200 120.0
180.0 297.64 A8 3150 75.0
140.0 169.93 A6 1807 79.8 70.45 Cool 4 1193 40.0 0.6667
220.0 39.05 A2 875 202.5 660.00 A5 4125 120.0
180.0 291.67 A10 4375 55.0
200.0 482.84 A3 3793 73.6 35.62 Cool 7 407 60.0 0.3333
120.0 159.19 A9 875 111.3 43.55 A11 865 102.6 469.74 Cool 8 6260 40.0 0.4000
230.0 0.500 A1 1993 130.4 0.500 A6 1807 40.0
220.0 0.500 A4 7200 100.0
190.0 0.667 A2 875 165.0 1.000 A10 4375 40.0
190.0 0.667 A12 407 176.4 0.333 A3 3793 50.0
1.000 A8 3150
250.0 65.67 Heat 5 4835 0.667 169.4 64.4 0.400 A11 865 50.0
1.000 A7 3150
190.0 0.500 A5 4125 107.5 0.333 A9 875 90.0
250.0 63.08 Heat 7 5400 160.0 0.750

Figure 16.7