Pinch Analysis with crisscross optimization prior to design

Case 10 - Example from Wu Xiao et al.

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Case 10 is a larger scale example with 10 hot streams, 10 cold streams, one hot and one cold utility. It was originally set up by Wu Xiao et al. for illustrating a new procedure based on Stream Pseudo Temperatures. Wu Xiao developed a network using multi-stream heat exchangers. The example was then used by Xing Luo and Georg Fieg et al. for illustrating the capabilities of a hybrid genetic algorithm for synthesis of heat exchanger networks. By its size as well as by the characteristics of the stream data, it is an example that is even much more challenging than example number 5 from Björk and Pettersson.

Stream data are given in Table 10.1.

Trade-off between energy and capital is shown in Figure 10.1 where classic analysis is labelled as ñClassicò (one system above the pinch and one system below the pinch). If one single system is assumed, then the total number of units is lower than with a pinch based design (21 instead of 36), leading to much lower cost, as shown in the curve labelled as ñC w/o Pinchò

The impact of the difference in heat transfer values on the required surface area is significant (Figure 10.2) and offers ample opportunities for crisscross. Whilst classic trade-off based on one single system would suggest a cost optimum of 2060 kEUR at 10.6 MW, crisscross analysis assuming one single system shows an optimum of only 1763 kEUR for a heating load of 8.75 MW. With crisscross analysis, the energy target is 20% lower and the cost target is 14% lower. As demonstrated by the various such networks that were developed, that much lower and also much more challenging cost target is also achievable.

Next to the shift values used by Wu Xiao, also optimum shift values using crisscross for a heat input of 8.75 MW are shown in Table 10.1. The very large shift on hot stream H6 will cause all heat of that stream being dumped into the cooling water; that also appears to be the best solution although classic pinch analysis would have suggested to integrating 75% of that heat load with cold streams. The effect of shifting H6 on required surface area is impressive and enables the total required surface area to be reduced by 30% (Figure 10.3).

The problem was solved in a stepwise approach. After each step a new analysis was run and the resulting grid was reduced to 4 integration bands. Then, out of the many alternatives, a new match was chosen that would fit in the temperature profile without violating pinch rules.

As shown in Figure 10.4 there is no sharp pinch and, consequently, classic pinch design rules are not appropriate. In order to avoid stream splits at the pinch, matches are sought that spread across the

pinch without giving away too much driving force. For minimizing the number of units, streams with the smallest heat loads preferably are satisfied with one single heat exchanger.
The above rules lead to the following steps:

- H6 on cooler
- H5 on C6 and C7 plus heater of 800 kW on C6
- H3 on C9 (both H1 and H3 are candidates; H1, however, would generate a pinch penalty of 869 kW whilst the penalty with H3 is only 299 kW)
- H4 on C10 plus cooler of 1050 kW
- H8 plus heater of 1350 kW on C3.

The original composite curves (shifted) and those of the remaining problem are shown in Figure 10.4 and Figure 10.5. The remaining data set shows a more pronounced pinch at the cold stream temperature of 120 °C. The remaining grid, reduced to 4 integration bands, is shown in Table 10.2.

Notwithstanding elimination of 10 out of the 20 streams in a first phase, network design for the integration bands 2 and 3 is still challenging. In both bands several networks are possible, each with the minimum area and minimum cost, or with hardly different area and cost. In the course of the study, 8 networks were identified in band 2 and 6 networks in band 3, leading to 48 possible combinations and it is very likely that the number of potentially interesting networks is even (much) higher.

As can be seen in Table 10.2 the possibility for a cooler on H1 was still maintained. Such cooler, however, is not necessarily required for making a feasible network and there are further options such as moving the cooling load to the cooler on stream H7 or to the cooler on stream H10 or spreading the load on both the coolers of H7 and H10. Each option will generate various possible initial networks for band 3 and each of them can be combined with any option for band 2 leading to a few hundred potentially interesting combinations in total. Keeping in mind that the complexity of the problem was already reduced drastically it would seem wise not to tackle this kind of problems without a minimum of insight in network characteristics.

The first objective used in this approach is minimum area simultaneously with minimum number of units in each integration band. This can be analyzed using loop optimization or, and even much faster, with LP programming. Although the Simplex method might fail, appropriate more sophisticated algorithms will do. The next objective is to adjust the minimum area network further into a minimum cost network by shifting loads from one band into another and creating independent systems within each band. If, as is mostly the case, the cost relation is not linear then LP cannot be used for this step. In cases with sub-optima like this one, even NLP might fail.

A final optimization strategy can now be applied, consisting in exploring a stream with 2 or more than 2 heat exchangers and swapping one load on the opposite side with the load on another stream on the opposite side in order to get 2 heat exchangers in series on the stream explored, allowing the merger of these into one single heat exchanger.

The results of the study on this example are summarized in Table 10.3 and compared with published results from other authors. Several networks could be developed with only one stream split. Eliminating the stream split would generate only a limited area penalty, the cost of which would be overcompensated by avoiding the split (the cost of the split was not considered explicitly) and, therefore, the networks with no split would be the more attractive ones.

Energy consumption of the best networks is very close to the targeted optimum from the trade-off analysis with crisscross optimization and the total cost is even lower (cfr. Figure 10.1).

For this example, due to the specifics of the stream data (various streams with same U, same mcp, same temperatures) a large number of networks can be developed with near optimum cost.

The best network with 22 units and 1 split is shown in Figure 10.6, the one without splits is shown in Figure 10.7. The networks without splits with 23, respectively 21 units are shown in Figure 10.8 and Figure 10.9; the networks with splits can easily be derived from the networks without splits by splitting hot stream H5.

The networks developed following the above procedure have lower cost and have a simpler structure than those obtained by other authors.

Table 10.1

Tsupply	Ttarget	Heat	U*f	Descript.	Optimum shift		mcp
					Wu Xiao (*)	Declercq	
°C	°C	kW	kW/K,m²	-	K	K	kW/K
180	75	3150	2.00	H1	6.7	0	30.0
280	120	2400	0.60	H2	13.2	8	15.0
180	75	3150	0.30	H3	22.9	19	30.0
140	45	2850	2.00	H4	9.8	0	30.0
220	120	2500	0.08	H5	46.4	46	25.0
180	55	1250	0.02	H6	89.0	124	10.0
170	45	3750	2.00	H7	10.6	0	30.0
180	50	3900	1.50	H8	12.7	2	30.0
280	90	2850	1.00	H9	13.2	4	15.0
180	60	3600	2.00	H10	5.7	0	30.0
40	230	3800	1.50	C1	15.1	1	20.0
120	260	4900	2.00	C2	16.3	0	35.0
40	190	5250	1.50	C3	4.2	1	35.0
50	190	4200	2.00	C4	13.5	0	30.0
50	250	4000	2.00	C5	15.4	0	20.0
40	150	1100	0.06	C6	68.7	65	10.0
40	150	2200	0.40	C7	21.0	13	20.0
120	210	3150	1.50	C8	16.2	1	35.0
40	130	3150	1.00	C9	4.5	4	35.0
60	120	1800	0.70	C10	5.6	6	30.0
325	325	8750	1.00	Heating		0	
25	40	4600	2.00	Cooling		0	

Heating 70/kW,y - Cooling 10/kW,y
Annual HEX cost = 8000 + 800 x $A^{0.8}$

(*) Stream pseudo temperature method and using multistream HEX

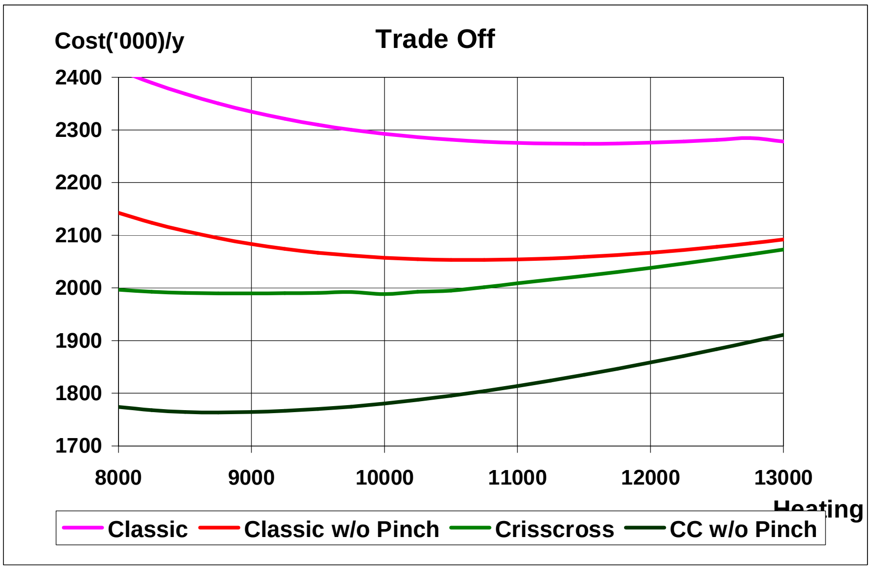


Figure 10.1

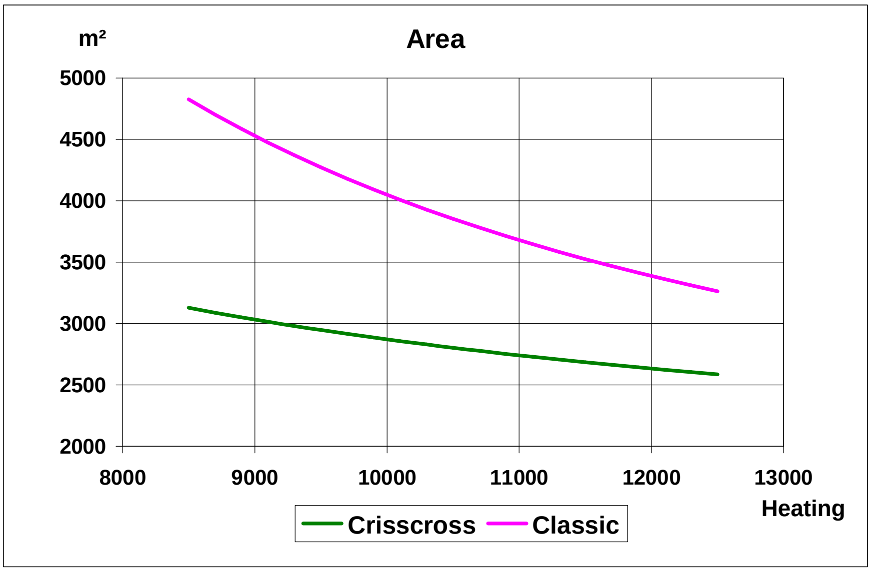


Figure 10.2

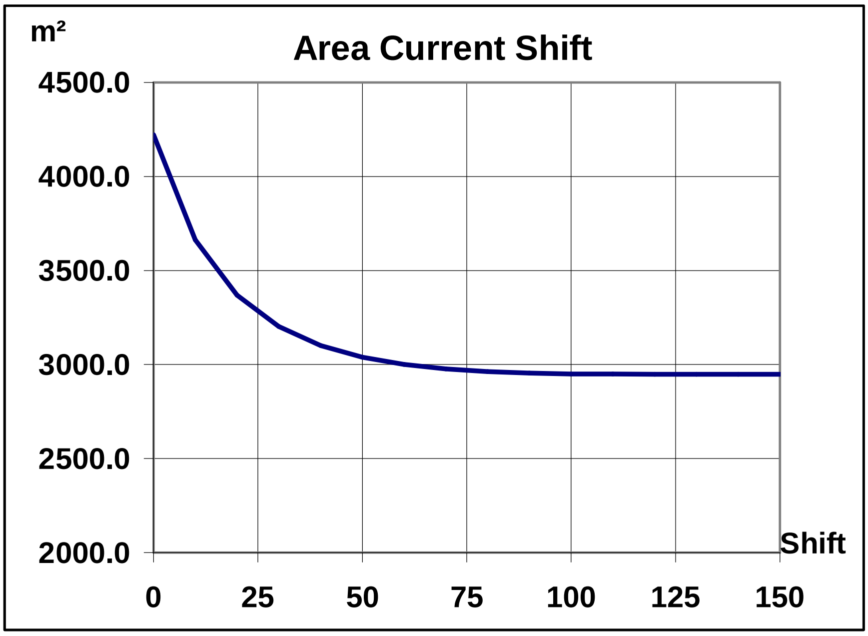


Figure 10.3

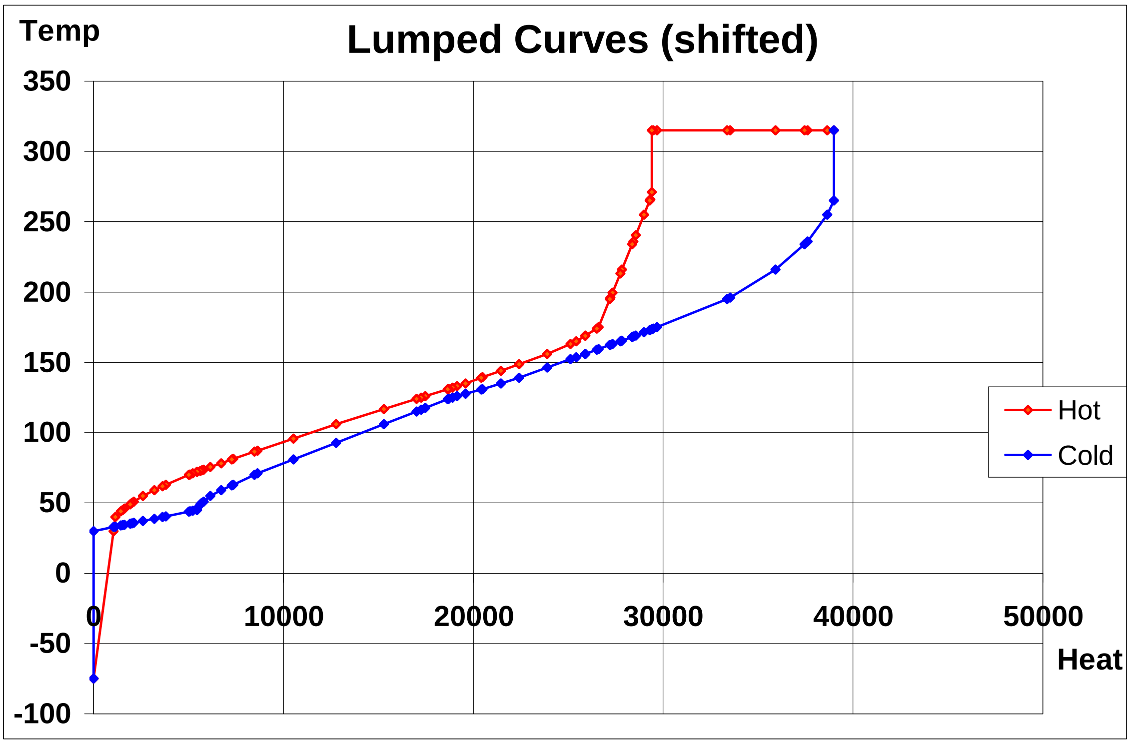


Figure 10.4

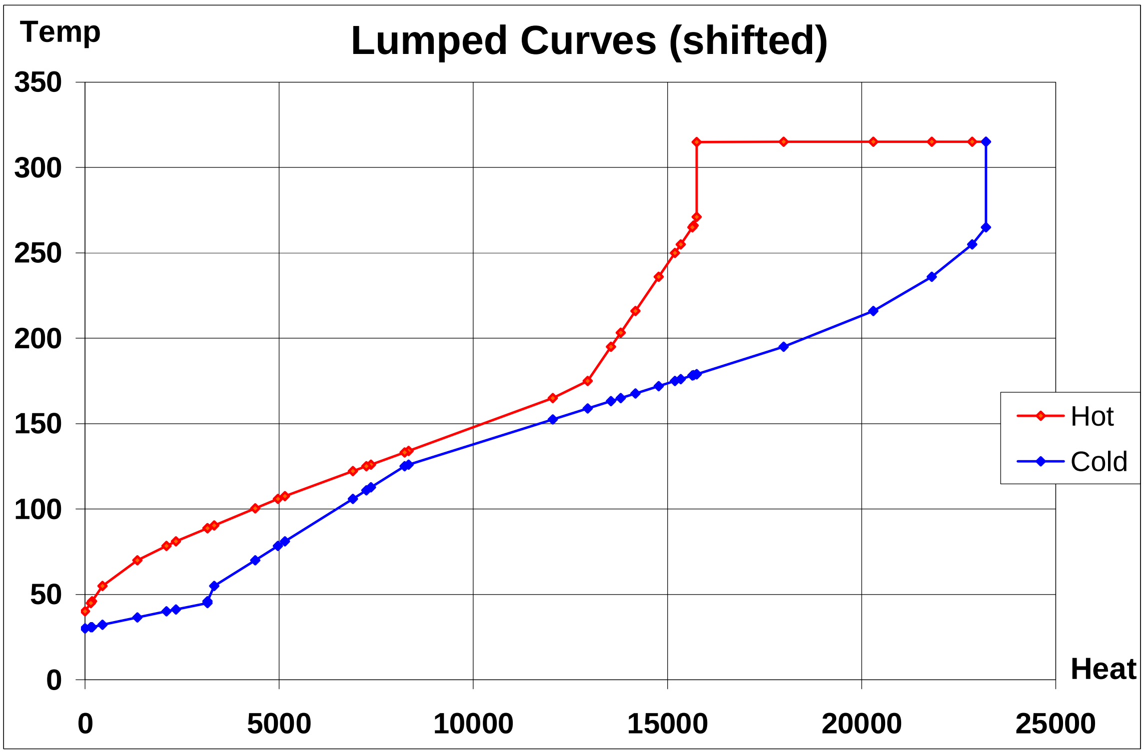


Figure 10.5

Table 10.2

Process : 10H + 10C

Heating target 8750 kW

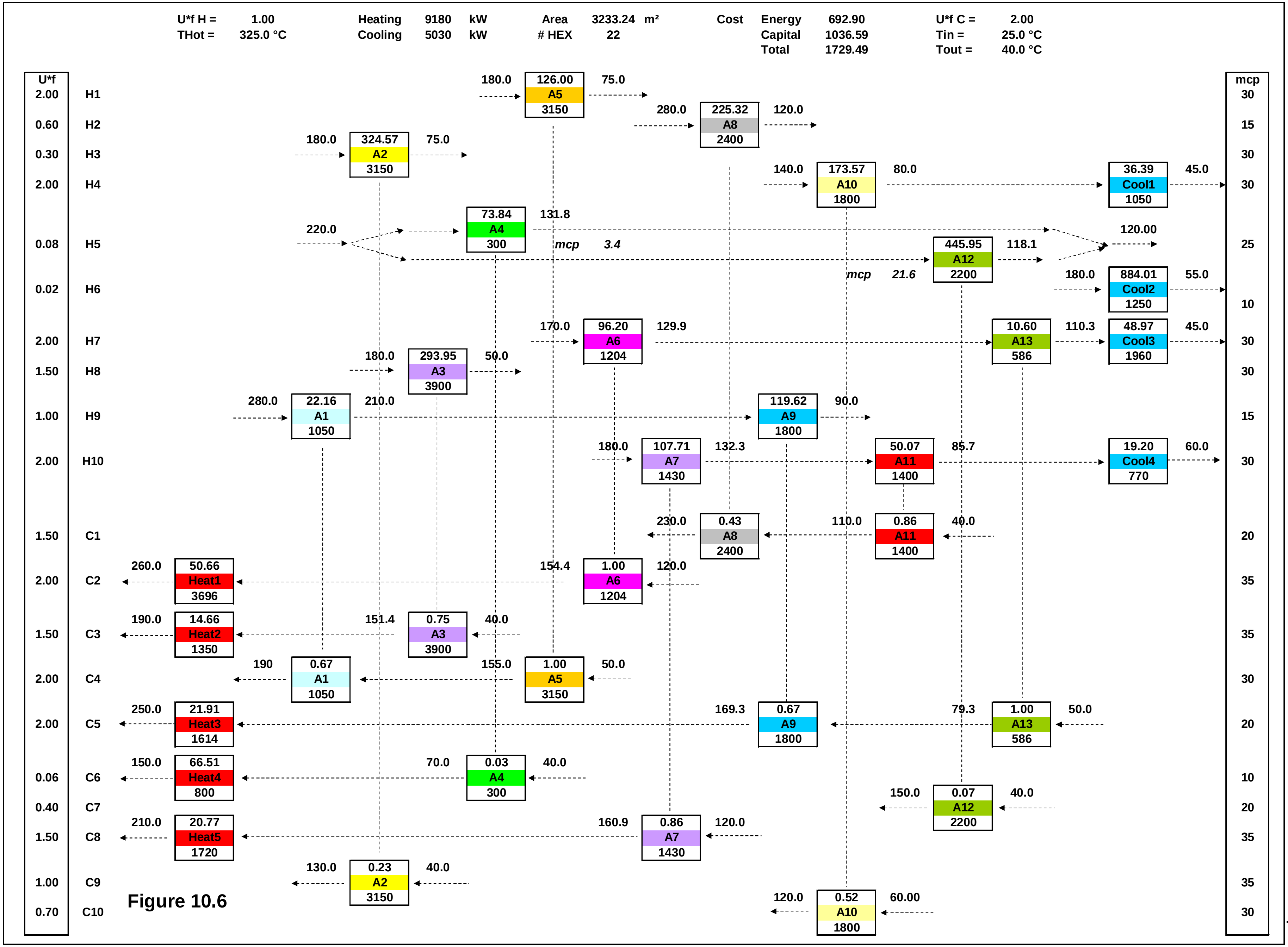
done : H6 on Cooler
H5 on C6 and C7 + Heater 800 kW on C6
H3 on C9
H4 on C10 + Cooler 1050 kW
H8 plus Heater 1350 kW on C3

Descriptio	Tsupply	Ttarget	U*f	mcp	Temp Grid		PINCH		
				DeltaTS	50.1	10.3	1.4	34.6	10.0
-	°C	°C	kW/m²,K	kW/K	°C				
Heating	325	325	1.00	74500.00	325.10	325.00			
H1	180	75	2.00	30		180.00	132.38	85.56	75.00
H2	280	120	0.60	15	280.00	187.00	139.38	120.00	
H7	170	45	2.00	30		170.00	132.38	85.56	45.00
H9	280	90	1.00	15	280.00	183.00	135.38	90.00	
H10	180	60	2.00	30		180.00	132.38	85.56	60.00
C1	40	230	1.50	20	230.00	158.68	120.00	40.00	
C2	120	260	2.00	35	260.00	159.68	120.00		
C4	50	190	2.00	30	190.00	159.68	122.17	50.00	
C5	50	250	2.00	20	250.00	159.68	121.00	50.00	
C8	120	210	1.50	35	210.00	158.68	120.00		
Cooling	25	40	2.00	210				40.00	25.00

Table 10.3

Optimum HEN's	QHot (MW)	Area (m²)	Cost ('000)	# HEX	# Splits
Published					
Wu Xiao (2006)	9016.0	3229.0	1827.77	29 (*)	
Xing Luo, Fieg et al. (2009)	9513.5	3039.0	1753.27	26	2
Laukkanen (2012)	9500.0	3083.9	1739.78	24	2
This research (2013)	9180.0	3233.2	1729.49	22	1
	9180.0	3250.9	1731.10	22	0
	8895.0	3289.3	1732.00	23	1
	8895.0	3307.0	1733.61	23	0
	9760.0	3163.9	1745.86	21	1
	9760.0	3181.6	1747.47	21	0

(*) 14 of which multi-stream HEX


U*f H = 1.00
THot = 325.0 °C
Heating 9180 kW
Cooling 5030 kW
Area 3233.24 m²
HEX 22
Cost
Energy 692.90
Capital 1036.59
Total 1729.49
U*f C = 2.00
Tin = 25.0 °C
Tout = 40.0 °C
U*f
mcp
2.00 H1 30
0.60 H2 15
0.30 H3 30
2.00 H4 30
0.08 H5 25
0.02 H6 10
2.00 H7 30
1.50 H8 30
1.00 H9 15
2.00 H10 30
1.50 C1 20
2.00 C2 35
1.50 C3 35
2.00 C4 30
2.00 C5 20
0.06 C6 10
0.40 C7 20
1.50 C8 35
1.00 C9 35
0.70 C10 30
180.0 126.00 A5 3150 75.0
280.0 225.32 A8 2400 120.0
180.0 324.57 A2 3150 75.0
140.0 173.57 A10 1800 80.0
36.39 Cool1 1050 45.0
73.84 A4 300 131.8
220.0
mcp 3.4
445.95 A12 2200 118.1
mcp 21.6
120.00
180.0 884.01 Cool2 1250 55.0
170.0 96.20 A6 1204 129.9
10.60 A13 586 110.3
48.97 Cool3 1960 45.0
180.0 293.95 A3 3900 50.0
280.0 22.16 A1 1050 210.0
119.62 A9 1800 90.0
180.0 107.71 A7 1430 132.3
50.07 A11 1400 85.7
19.20 Cool4 770 60.0
230.0 0.43 A8 2400
110.0 0.86 A11 1400 40.0
260.0 50.66 Heat1 3696
154.4 1.00 A6 1204 120.0
190.0 14.66 Heat2 1350
151.4 0.75 A3 3900 40.0
190 0.67 A1 1050
155.0 1.00 A5 3150 50.0
250.0 21.91 Heat3 1614
169.3 0.67 A9 1800
79.3 1.00 A13 586 50.0
150.0 66.51 Heat4 800
70.0 0.03 A4 300 40.0
150.0 0.07 A12 2200 40.0
210.0 20.77 Heat5 1720
160.9 0.86 A7 1430 120.0
130.0 0.23 A2 3150 40.0
120.0 0.52 A10 1800 60.00
Figure 10.6

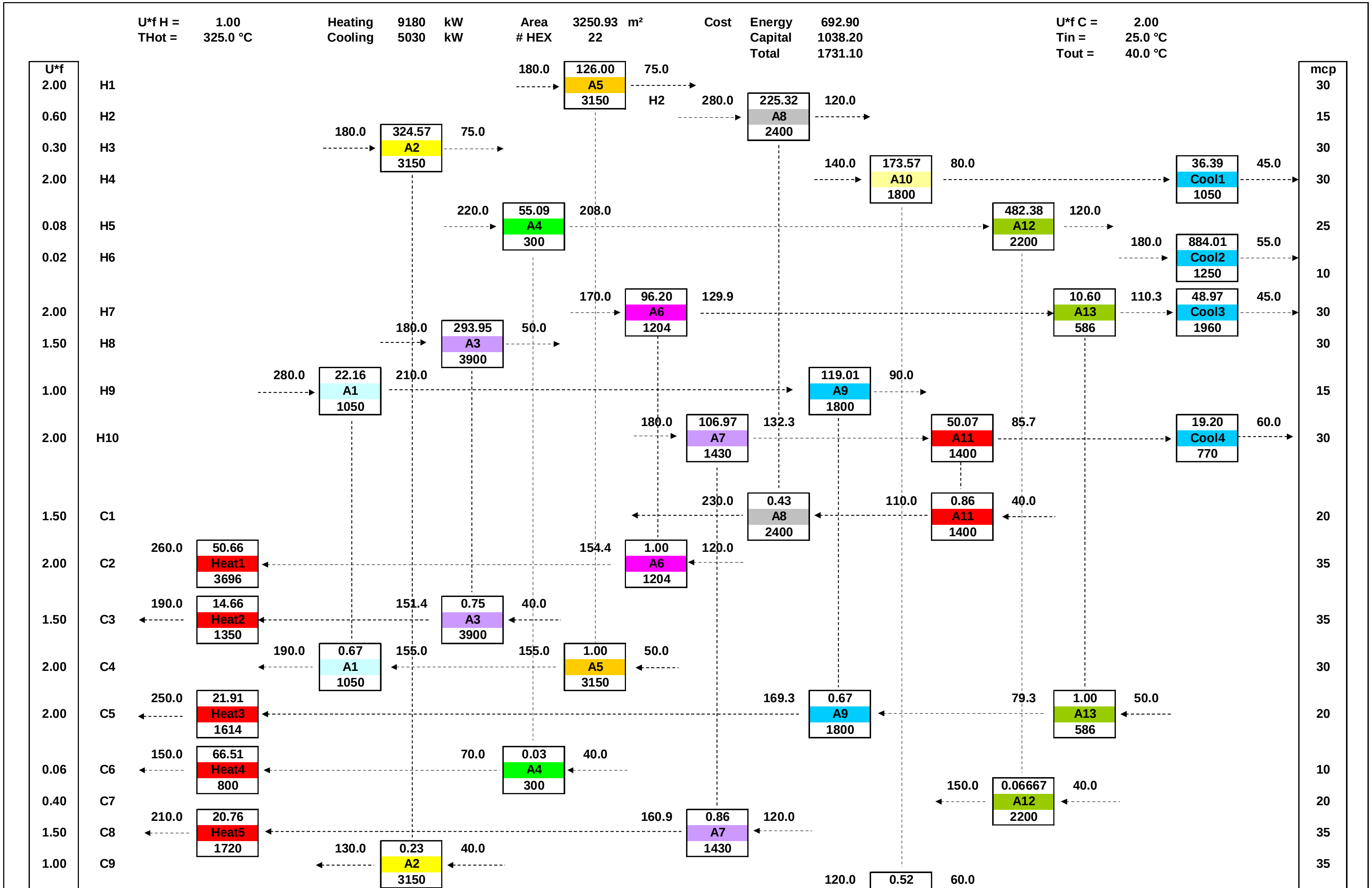

U*f H = 1.00
THot = 325.0 °C
Heating 9180 kW
Cooling 5030 kW
Area 3250.93 m²
HEX 22
Cost
Energy 692.90
Capital 1038.20
Total 1731.10
U*f C = 2.00
Tin = 25.0 °C
Tout = 40.0 °C
U*f
mcp
2.00 H1 30
0.60 H2 15
0.30 H3 30
2.00 H4 30
0.08 H5 25
0.02 H6 10
2.00 H7 30
1.50 H8 30
1.00 H9 15
2.00 H10 30
1.50 C1 20
2.00 C2 35
1.50 C3 35
2.00 C4 30
2.00 C5 20
0.06 C6 10
0.40 C7 20
1.50 C8 35
1.00 C9 35
0.70 C10 30
180.0
126.00
A5
3150
75.0
H2
280.0
225.32
A8
2400
120.0
180.0
324.57
A2
3150
75.0
140.0
173.57
A10
1800
80.0
36.39
Cool1
1050
45.0
220.0
55.09
A4
300
208.0
482.38
A12
2200
120.0
180.0
884.01
Cool2
1250
55.0
170.0
96.20
A6
1204
129.9
10.60
A13
586
110.3
48.97
Cool3
1960
45.0
180.0
293.95
A3
3900
50.0
280.0
22.16
A1
1050
210.0
119.01
A9
1800
90.0
180.0
106.97
A7
1430
132.3
50.07
A11
1400
85.7
19.20
Cool4
770
60.0
230.0
0.43
A8
2400
110.0
0.86
A11
1400
40.0
260.0
50.66
Heat1
3696
154.4
1.00
A6
1204
120.0
190.0
14.66
Heat2
1350
151.4
0.75
A3
3900
40.0
190.0
0.67
A1
1050
155.0
155.0
1.00
A5
3150
50.0
250.0
21.91
Heat3
1614
169.3
0.67
A9
1800
79.3
1.00
A13
586
50.0
150.0
66.51
Heat4
800
70.0
0.03
A4
300
40.0
150.0
0.06667
A12
2200
40.0
210.0
20.76
Heat5
1720
160.9
0.86
A7
1430
120.0
130.0
0.23
A2
3150
40.0
120.0
0.52
A10
1800
60.0

Figure 10.7

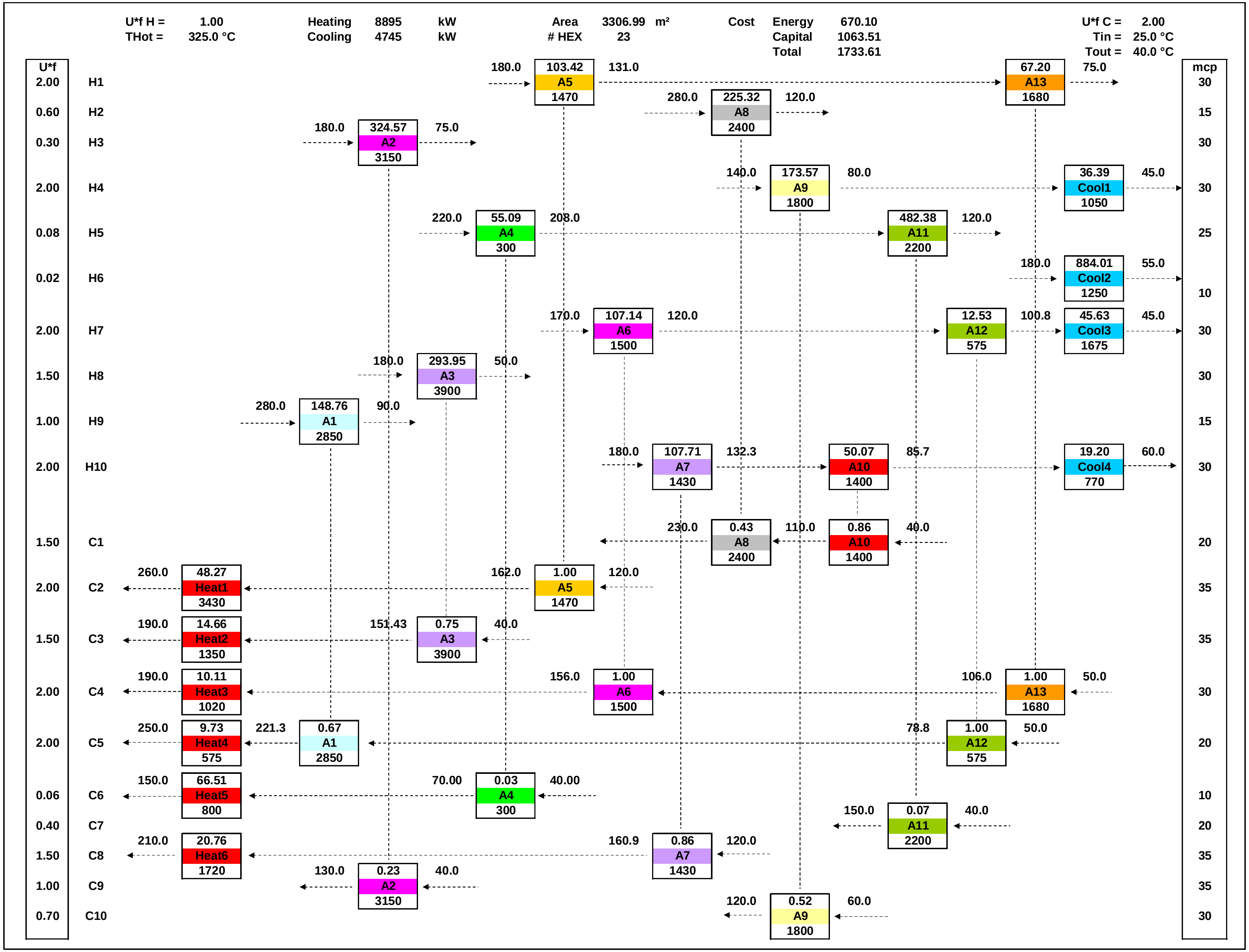

U*f H = 1.00
THot = 325.0 °C
Heating 8895 kW
Cooling 4745 kW
Area 3306.99 m²
HEX 23
Cost
Energy 670.10
Capital 1063.51
Total 1733.61
U*f C = 2.00
Tin = 25.0 °C
Tout = 40.0 °C
U*f
mcp
2.00 H1 30
0.60 H2 15
0.30 H3 30
2.00 H4 30
0.08 H5 25
0.02 H6 10
2.00 H7 30
1.50 H8 30
1.00 H9 15
2.00 H10 30
1.50 C1 20
2.00 C2 35
1.50 C3 35
2.00 C4 30
2.00 C5 20
0.06 C6 10
0.40 C7 20
1.50 C8 35
1.00 C9 35
0.70 C10 30
180.0 103.42 A5 1470 131.0
67.20 A13 1680 75.0
280.0 225.32 A8 2400 120.0
180.0 324.57 A2 3150 75.0
140.0 173.57 A9 1800 80.0
36.39 Cool1 1050 45.0
220.0 55.09 A4 300 208.0
482.38 A11 2200 120.0
180.0 884.01 Cool2 1250 55.0
170.0 107.14 A6 1500 120.0
12.53 A12 575 100.8
45.63 Cool3 1675 45.0
180.0 293.95 A3 3900 50.0
280.0 148.76 A1 2850 90.0
180.0 107.71 A7 1430 132.3
50.07 A10 1400 85.7
19.20 Cool4 770 60.0
230.0 0.43 A8 2400 110.0
0.86 A10 1400 40.0
260.0 48.27 Heat1 3430
162.0 1.00 A5 1470 120.0
190.0 14.66 Heat2 1350
151.43 0.75 A3 3900 40.0
190.0 10.11 Heat3 1020
156.0 1.00 A6 1500
106.0 1.00 A13 1680 50.0
250.0 9.73 Heat4 575
221.3 0.67 A1 2850
78.8 1.00 A12 575 50.0
150.0 66.51 Heat5 800
70.00 0.03 A4 300 40.00
150.0 0.07 A11 2200 40.0
210.0 20.76 Heat6 1720
160.9 0.86 A7 1430 120.0
130.0 0.23 A2 3150 40.0
120.0 0.52 A9 1800 60.0

Figure 10.8

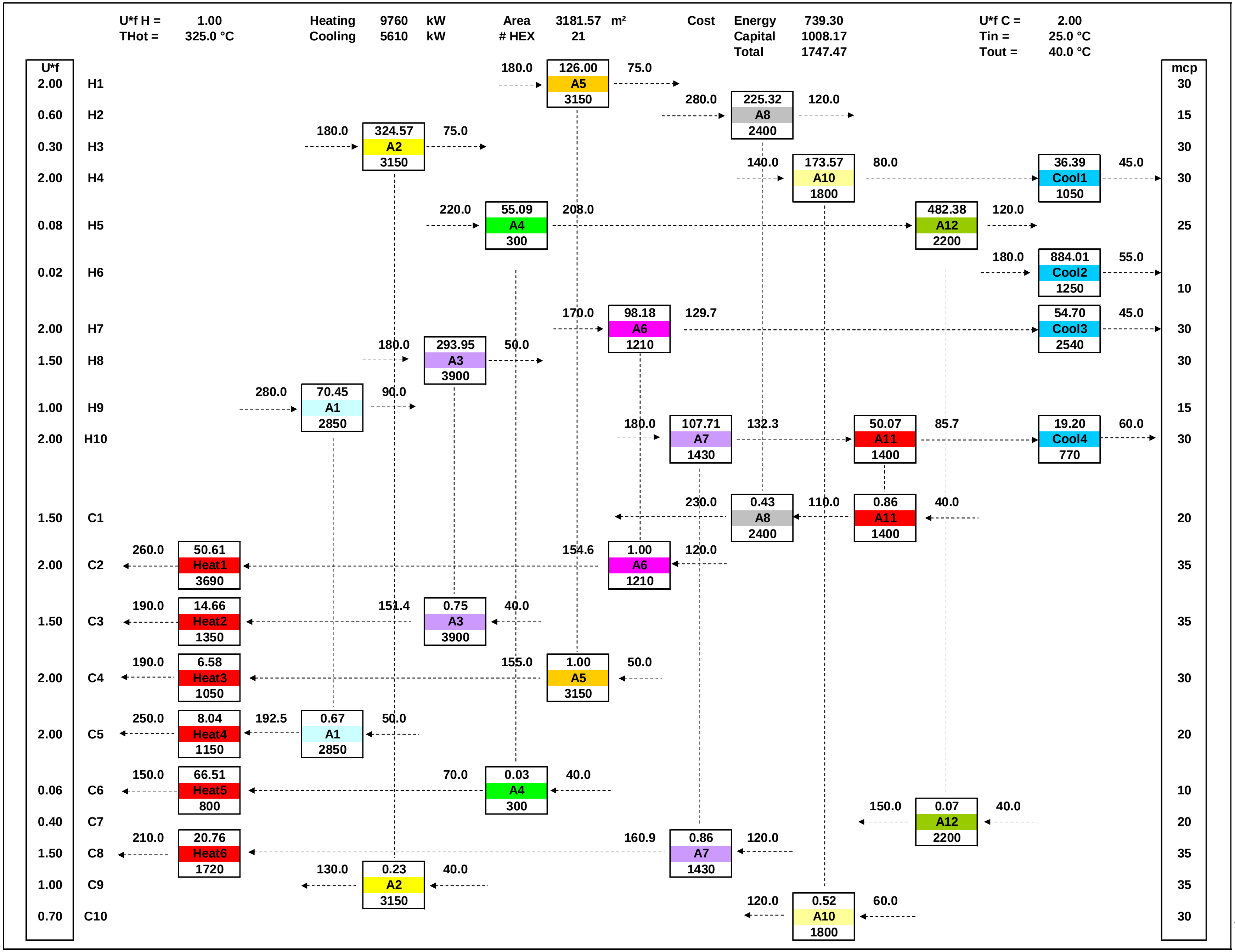

U*f H = 1.00
THot = 325.0 °C
Heating 9760 kW
Cooling 5610 kW
Area 3181.57 m²
HEX 21
Cost
Energy 739.30
Capital 1008.17
Total 1747.47
U*f C = 2.00
Tin = 25.0 °C
Tout = 40.0 °C
U*f
mcp
H1
H2
H3
H4
H5
H6
H7
H8
H9
H10
C1
C2
C3
C4
C5
C6
C7
C8
C9
C10
A1
A2
A3
A4
A5
A6
A7
A8
A10
A11
A12
Cool1
Cool2
Cool3
Cool4
Heat1
Heat2
Heat3
Heat4
Heat5
Heat6

Figure 10.9