Pinch Technology Second Generation

Analysis with crisscross optimisation prior to design

Design with loop optimisation for minimum area and minimum cost

Example Case 3

Example from Colberg and Morari

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Case 3 – Example from Colberg and Morari

Case 3, a 7-stream problem, was originally treated by Colberg & Morari (1990) and by Yee and Grossmann (1990) and was studied many times thereafter. The data are given in Table 3.1.

Table 3.1

Tsupply °C	Ttarget °C	Heat kW	Shift K	U*f kW/K,m²	Description -
353	313	392.08	0.0	1.25	H1
347	246	296.03	36.0	0.05	H2
255	80	1078.18	0.0	3.20	H3
224	340	832.76	4.0	0.65	C1
116	303	119.87	11.0	0.25	C2
53	113	457.62	14.0	0.33	C3
40	293	427.57	0.0	3.20	C4
377	377	244.13	0.0	3.50	Heating
20	35	172.60	0.0	3.50	Cooling

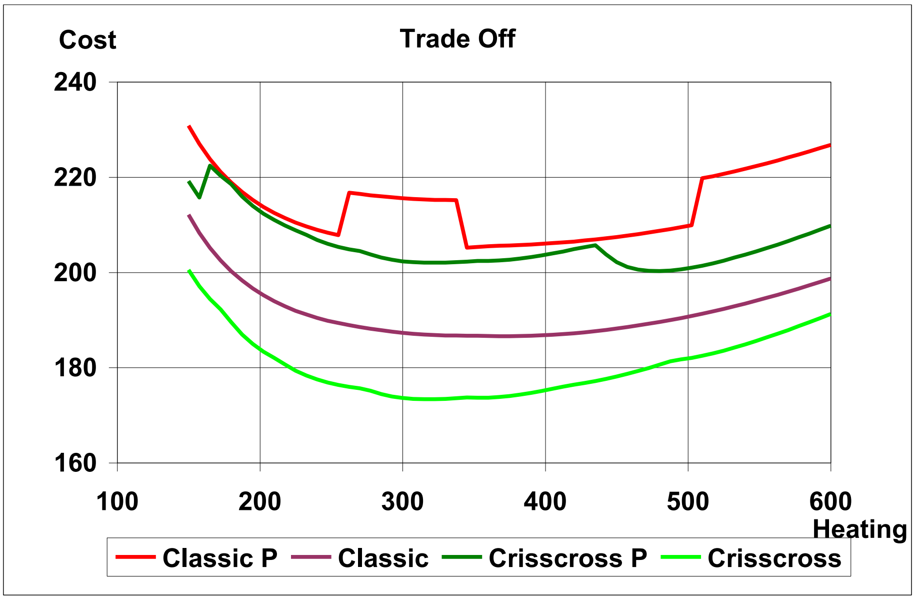
Annual Cost Heating : 130/kW Cooling : 20/kW
Annual HEX cost = 8600 + 670 x $A^{0.83}$

Energy targets for DTMin global of 20 K; Shift optimised for minimum area

Shift C3 reduced from 50K to 14K in order to reduce the number of integration bands

Since only investment cost figures have been published, the analysis was first made with energy targets corresponding with the reported 20 K DTMin. It should be mentioned however that this value might correspond to a local suboptimum as can be concluded from the trade-off curve in Fig. 3.1 which was calculated with reasonable energy cost figures.

Fig.3.1



If trade-off is done assuming pinch design with a network above and one below the pinch, then the curves show a discontinuity occurring when a particular stream starts or stops crossing the pinch at particular integration. If only one single system is assumed, then there are no discontinuities in the trade-off curve.

Classic analysis results into a surface area target of 227.03 m². With crisscross optimisation, this area target is reduced to 185.50 m². Relaxation of the shift on cold stream C3 from 50 K to 14 K reduces the number of integration bands (superstructures) and the complexity of the initial network whilst incurring only a small increase of the surface area to 186.86 m².

The effect of various combinations of stream shifts on the area target is shown in Fig. 3.2. As a result of crisscross, a given integration can be realised with less surface which means that the feasibility area is increased. This can no longer be expressed as a function of DTMin since a uniform DTMin does no longer exist, but now this feasibility area can be shown as a function of the integration or as a function of the hot utility requirement as shown in Fig.3.3.

Example Colberg & Morari – Surface area crisscrossing streams 4 and 5

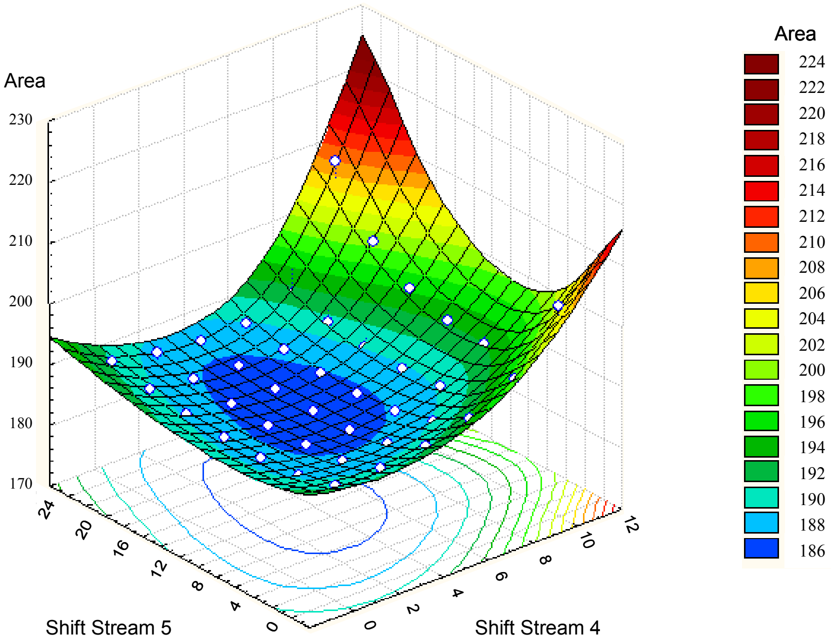


Fig.3.2

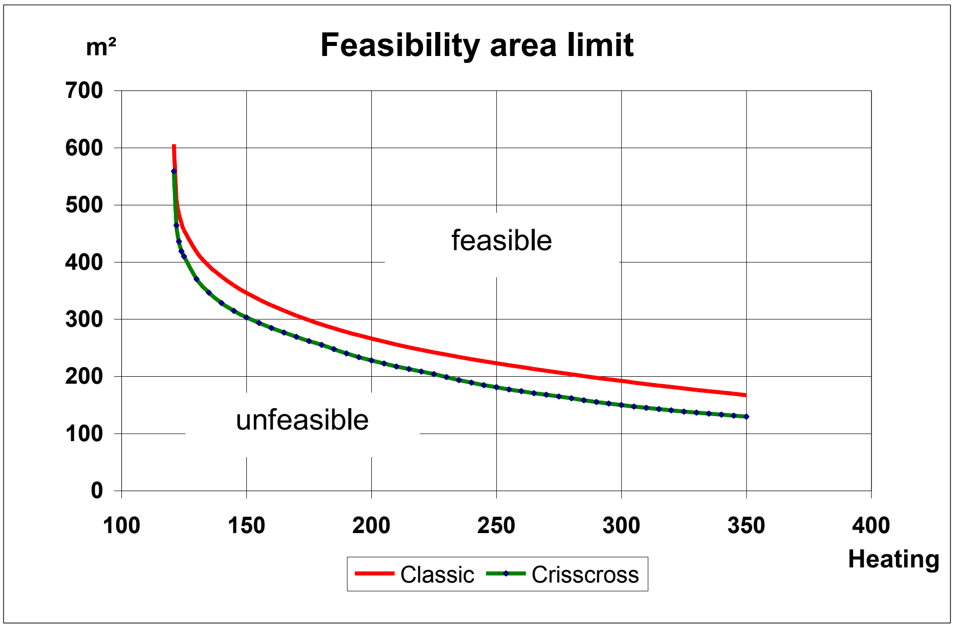


Fig.3.3

Using the grid diagram resulting from the classic pinch analysis leads to the initial HEN of Fig. 3.4. This initial network shows two topology traps, one of which (HEX B1) cannot be avoided without heavy energy penalty. Indeed, this load below the pinch must be satisfied from the only available hot stream H3 below the pinch whilst HEX B1 does not fit into the optimum HEN as will be shown later.

The crisscross procedure generates a grid diagram as shown in the upper part of Table 3.2 containing 11 vertical integration bands (superstructures). With this input, the design program calculates an area of 181.97 m² for 24 heat exchangers. This area is lower than what was targeted. Indeed, the area in the targeting procedure is calculated on the basis of a spaghetti network whilst the design program develops a network with minimum area and minimum number of units at the same time. The network obtained could now be further developed by reducing the number of units. It is more appropriate, however, to reduce the number of integration bands as far as possible by merging adjacent bands prior to structuring the flow sheet of the HEN. This is possible as long as there are no temperature constraints (the design program assumes isothermal split). If merging of bands is no longer possible, then small heat exchangers can be merged individually with units on the same process streams in the integration band upstream or downstream. Finally, heat exchange for a particular stream in a particular band can be blocked by imposing identical input and output temperatures on that stream. By using one or more of these techniques the number of integration bands (superstructures) can be reduced to 7, leading to the initial HEN of Fig.3.5 with 16 exchangers. This initial network shows no topology traps. Reducing the number of integration bands further to 6 leads to the grid diagram as shown in the lower part of Table 3.2 and to the initial HEN of Fig. 3.6 with 10 exchangers. This HEN is only a few small steps away from the final optimum HEN (Fig. 3.7) as developed by Anantharaman and Gundersen using a combination of LP, NLP and MILP procedures. Obviously, the HEN of Fig. 3.5 can also be developed into the HEN of Fig. 3.6 by evolution.

The size of a problem can often be reduced by applying heuristic rules to start with. “Satisfy the smallest heat load with one single heat exchanger” is very appropriate in this particular case, defining the crucial HEX A3 in the optimum HEN Fig. 3.7 from the very beginning. However, according to classic pinch analysis, this choice shall be rejected, since the remaining problem shows an energy penalty of 28% over the original Heating target; this is in line with the unavoidable topology trap in Fig. 3.4. On the other hand, analysis with crisscross optimisation shows no penalty and endorses the choice of A3.

The trade-off picture of Fig. 3.1 would suggest that a Heating load of 480 kW, respectively 320 kW would also deserve special attention.

Further analysis and design of the 480 kW cost minimum leads to the HEN of Fig. 3.8 (best of various options) with 2 independent systems, 7 units and an annual cost of 177.97 K at 440.68 kW Heating. This cost is 2.8 % lower than the cost of Fig. 3.7 which is 183.05 K.

Further analysis and design of the 320 kW cost minimum leads to HEN of Fig. 3.9 with 8 units and an annual cost of 175.59 K at 335.74 kW Heating. This cost is 4.1 % lower than the cost of Fig. 3.7 and this network is better than any proposal known so far. In view of the research already spent on this case during the past twenty years, this improvement is significant.

During the crisscross optimisation of the trade-off, it is not possible to transit from the minimum at 320 kW to the minimum at 480 kW across the intermediate maximum at 440 KW. This would suggest that there is a topology trap between the two scenarios. Comparison of the two final networks confirms that it is not possible to transit from one design to the other.

It is obvious that the configuration of the Grid Diagram at the start of the procedure is decisive for the outcome. Therefore, limits and the number of the integration bands which form the superstructure should not be chosen at random but should be defined carefully.

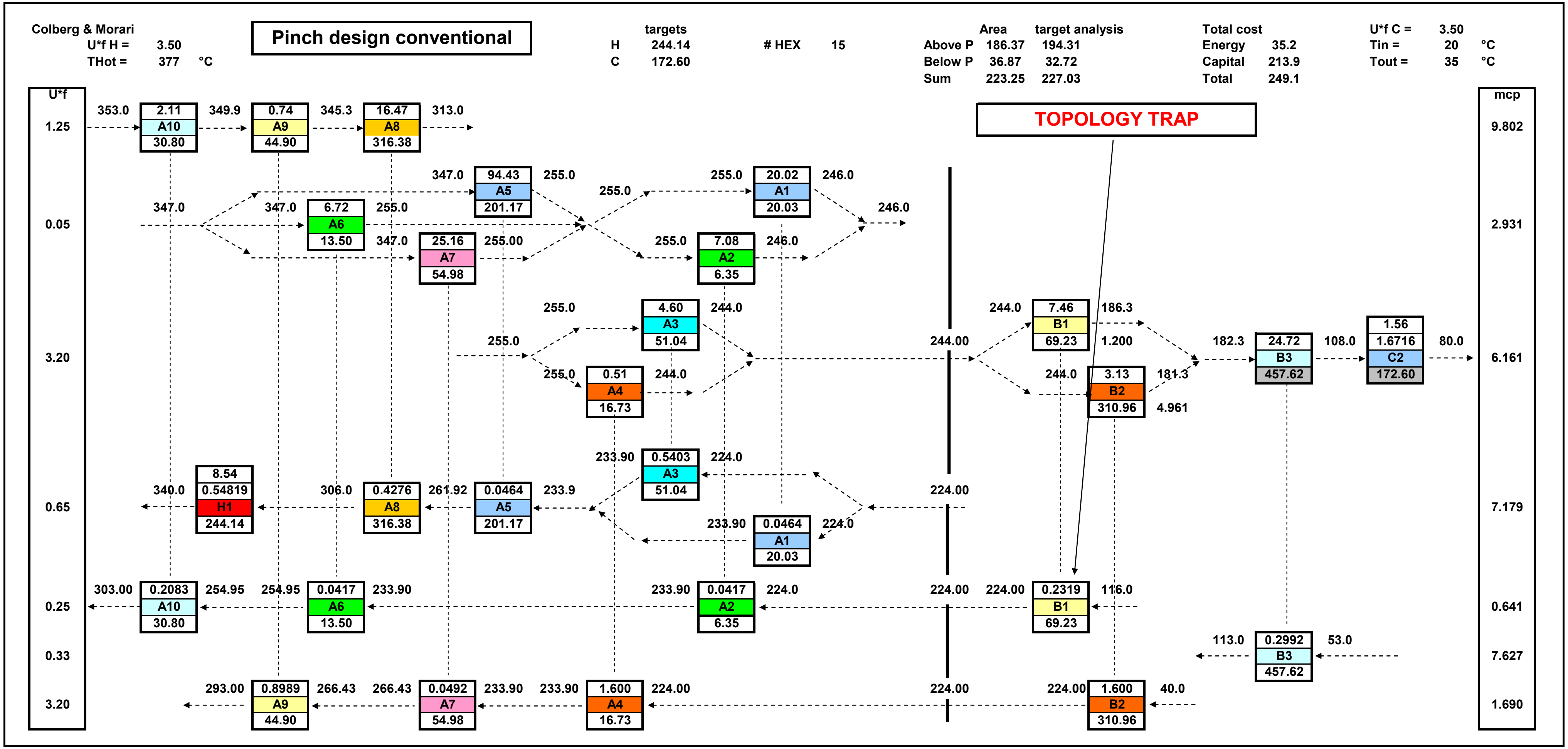

Colberg & Morari
U*f H = 3.50
THot = 377 °C
Pinch design conventional
targets
H 244.14
C 172.60
HEX 15
Area
target analysis
Above P 186.37 194.31
Below P 36.87 32.72
Sum 223.25 227.03
Total cost
Energy 35.2
Capital 213.9
Total 249.1
U*f C = 3.50
Tin = 20 °C
Tout = 35 °C
U*f
mcp
1.25
9.802
0.05
2.931
3.20
6.161
0.65
7.179
0.25
0.641
0.33
7.627
3.20
1.690
TOPOLOGY TRAP
353.0
2.11
A10
30.80
349.9
0.74
A9
44.90
345.3
16.47
A8
316.38
313.0
347.0
94.43
A5
201.17
255.0
255.0
20.02
A1
20.03
246.0
347.0
347.0
6.72
A6
13.50
255.0
255.0
246.0
347.0
25.16
A7
54.98
255.00
255.0
7.08
A2
6.35
246.0
255.0
4.60
A3
51.04
244.0
255.0
255.0
0.51
A4
16.73
244.0
244.00
244.0
7.46
B1
69.23
186.3
1.200
244.0
3.13
B2
310.96
181.3
4.961
182.3
24.72
B3
457.62
108.0
1.56
1.6716
C2
172.60
80.0
233.90
0.5403
A3
51.04
224.0
340.0
8.54
0.54819
H1
244.14
306.0
0.4276
A8
316.38
261.92
0.0464
A5
201.17
233.9
224.00
233.90
0.0464
A1
20.03
224.0
303.00
0.2083
A10
30.80
254.95
254.95
0.0417
A6
13.50
233.90
233.90
0.0417
A2
6.35
224.0
224.00
224.00
0.2319
B1
69.23
116.0
113.0
0.2992
B3
457.62
53.0
293.00
0.8989
A9
44.90
266.43
266.43
0.0492
A7
54.98
233.90
233.90
1.600
A4
16.73
224.00
224.00
224.00
1.600
B2
310.96
40.0

Fig.3.4

N°	DeltaTS	33.0		63.0		66.7		46.2		47.0		6.2		5.3		72.8		79.2		48.4		68.0		60.0
	DeltaQ		215.4		28.8		135.5		256.6		164.1		197.4		211.7		23.7		559.0		45.6		172.6	
	---------------------	1		2		3		4		5		6		7		8		9		10		11		
8		377.0		377.0		377.0																		
1						353.0		339.2		313.0														
2										347.0		291.0		269.3		246.0								
3												255.0		233.3		210.0		206.2		115.4		108.0		80.0
4		340.0		310.0		306.3		289.0		262.0		244.8		224.0										
5				303.0		299.3		282.0		255.0		237.8		217.0		126.2		116.0						
6																		113.0		53.0				
7								293.0		266.0		248.8		228.0		137.2		127.0		67.0		40.0		
9																						35.0		20.0

N°	DeltaTS	33.0	28.8	66.7	135.5	47.0		6.2	23.7	79.2	45.6	68.0		60.0
	DeltaQ		215.4		256.6		164.1		211.7		559.0		172.6	
	---------------------	1		2		3		4		5		6		
8		377.0		377.0										
1				353.0		313.0								
2						347.0		246.0						
3								255		233		108		80
4		340.0		306.0		261.8		237.3		224.0				
5						303.0		116.0						
6										113.0		53.0		
7				293.0		248.8		248.8		225.9		40.0		
9												35.0		20.0

Table 3.2

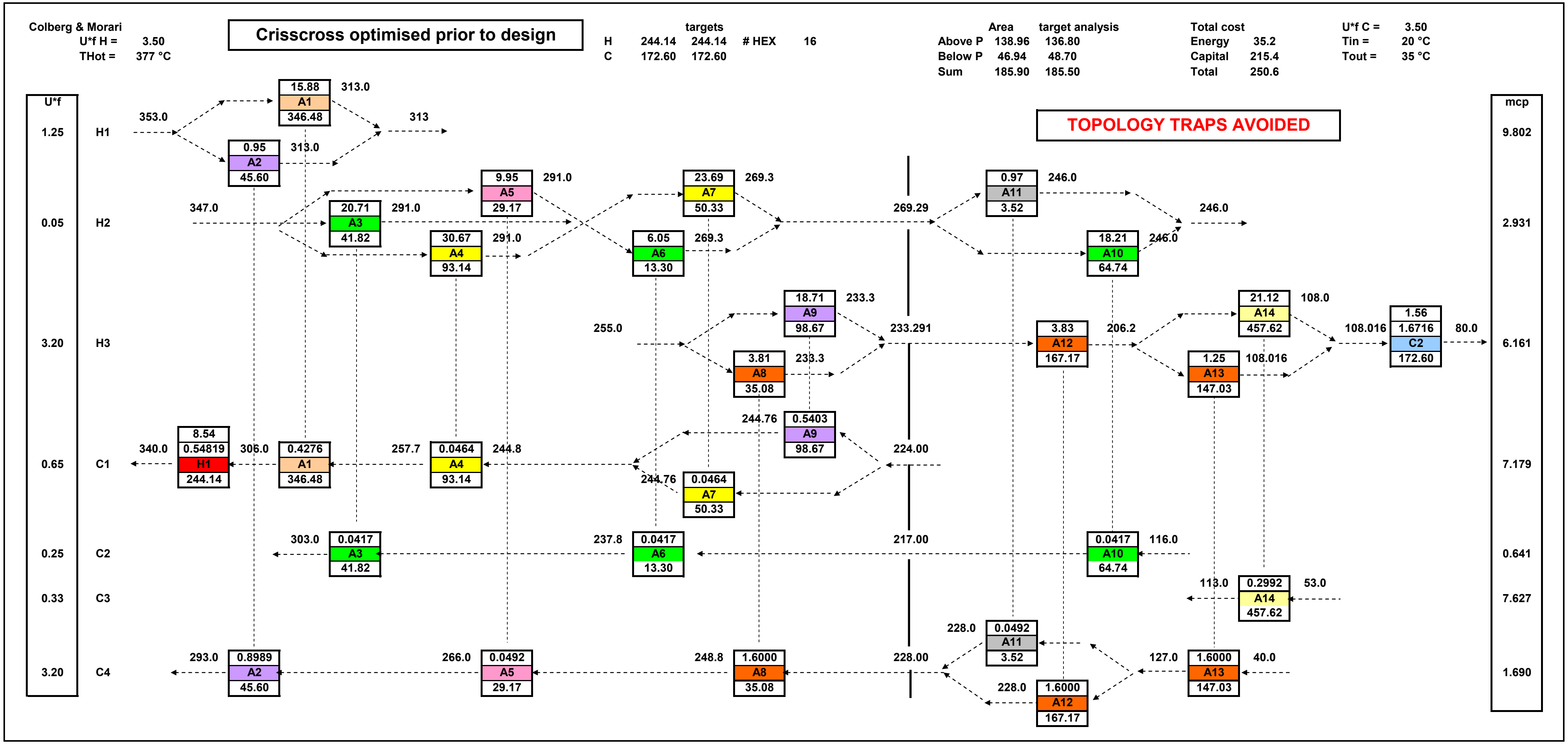

Colberg & Morari
U*f H = 3.50
THot = 377 °C
Crisscross optimised prior to design
targets
H 244.14 244.14 # HEX 16
C 172.60 172.60
Area target analysis
Above P 138.96 136.80
Below P 46.94 48.70
Sum 185.90 185.50
Total cost
Energy 35.2
Capital 215.4
Total 250.6
U*f C = 3.50
Tin = 20 °C
Tout = 35 °C
TOPOLOGY TRAPS AVOIDED
U*f
1.25
0.05
3.20
0.65
0.25
0.33
3.20
H1
H2
H3
C1
C2
C3
C4
mcp
9.802
2.931
6.161
7.179
0.641
7.627
1.690
353.0
15.88
A1
346.48
313.0
313
0.95
A2
45.60
313.0
347.0
20.71
A3
41.82
291.0
9.95
A5
29.17
291.0
30.67
A4
93.14
291.0
23.69
A7
50.33
269.3
6.05
A6
13.30
269.3
269.29
0.97
A11
3.52
246.0
246.0
18.21
A10
64.74
246.0
255.0
18.71
A9
98.67
233.3
3.81
A8
35.08
233.3
233.291
3.83
A12
167.17
206.2
21.12
A14
457.62
108.0
1.25
A13
147.03
108.016
108.016
1.56
1.6716
C2
172.60
80.0
340.0
8.54
0.54819
H1
244.14
306.0
0.4276
A1
346.48
257.7
0.0464
A4
93.14
244.8
244.76
0.5403
A9
98.67
224.00
244.76
0.0464
A7
50.33
303.0
0.0417
A3
41.82
237.8
0.0417
A6
13.30
217.00
0.0417
A10
64.74
116.0
113.0
0.2992
A14
457.62
53.0
228.0
0.0492
A11
3.52
293.0
0.8989
A2
45.60
266.0
0.0492
A5
29.17
248.8
1.6000
A8
35.08
228.00
228.0
1.6000
A12
167.17
127.0
1.6000
A13
147.03
40.0

Fig.3.5

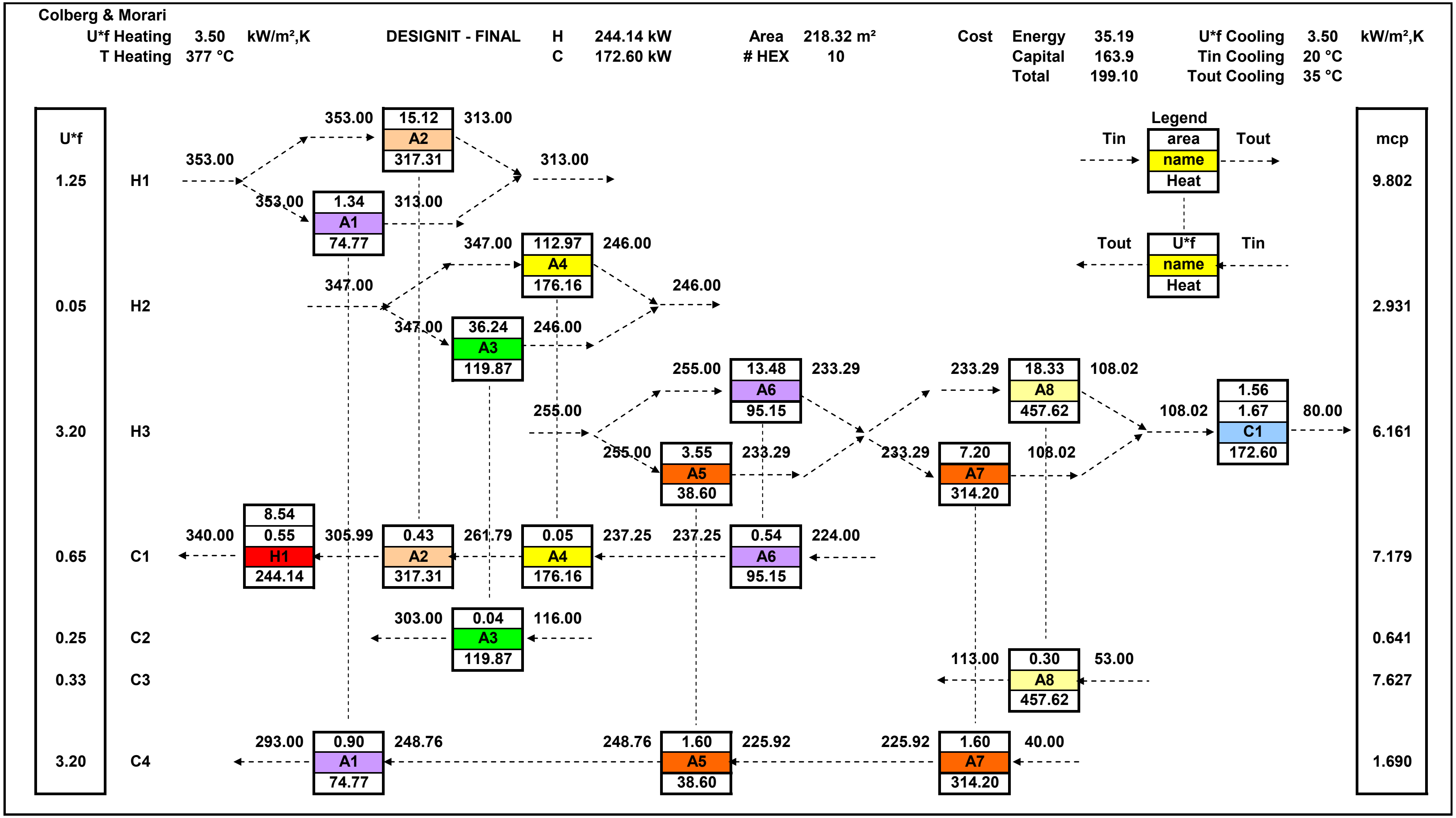

Colberg & Morari
U*f Heating 3.50 kW/m²,K
T Heating 377 °C
DESIGNIT - FINAL
H 244.14 kW
C 172.60 kW
Area 218.32 m²
HEX 10
Cost
Energy 35.19
Capital 163.9
Total 199.10
U*f Cooling 3.50 kW/m²,K
Tin Cooling 20 °C
Tout Cooling 35 °C
U*f
1.25
0.05
3.20
0.65
0.25
0.33
3.20
H1
H2
H3
C1
C2
C3
C4
mcp
9.802
2.931
6.161
7.179
0.641
7.627
1.690
353.00
15.12
A2
317.31
313.00
353.00
313.00
353.00
1.34
A1
74.77
313.00
347.00
112.97
A4
176.16
246.00
347.00
246.00
347.00
36.24
A3
119.87
246.00
255.00
13.48
A6
95.15
233.29
233.29
18.33
A8
457.62
108.02
255.00
255.00
3.55
A5
38.60
233.29
233.29
7.20
A7
314.20
108.02
108.02
1.56
1.67
C1
172.60
80.00
8.54
340.00
0.55
H1
244.14
305.99
0.43
A2
317.31
261.79
0.05
A4
176.16
237.25
237.25
0.54
A6
95.15
224.00
303.00
0.04
A3
119.87
116.00
113.00
0.30
A8
457.62
53.00
293.00
0.90
A1
74.77
248.76
248.76
1.60
A5
38.60
225.92
225.92
1.60
A7
314.20
40.00
Legend
Tin
area
name
Heat
Tout
Tout
U*f
name
Heat
Tin

Fig.3.6

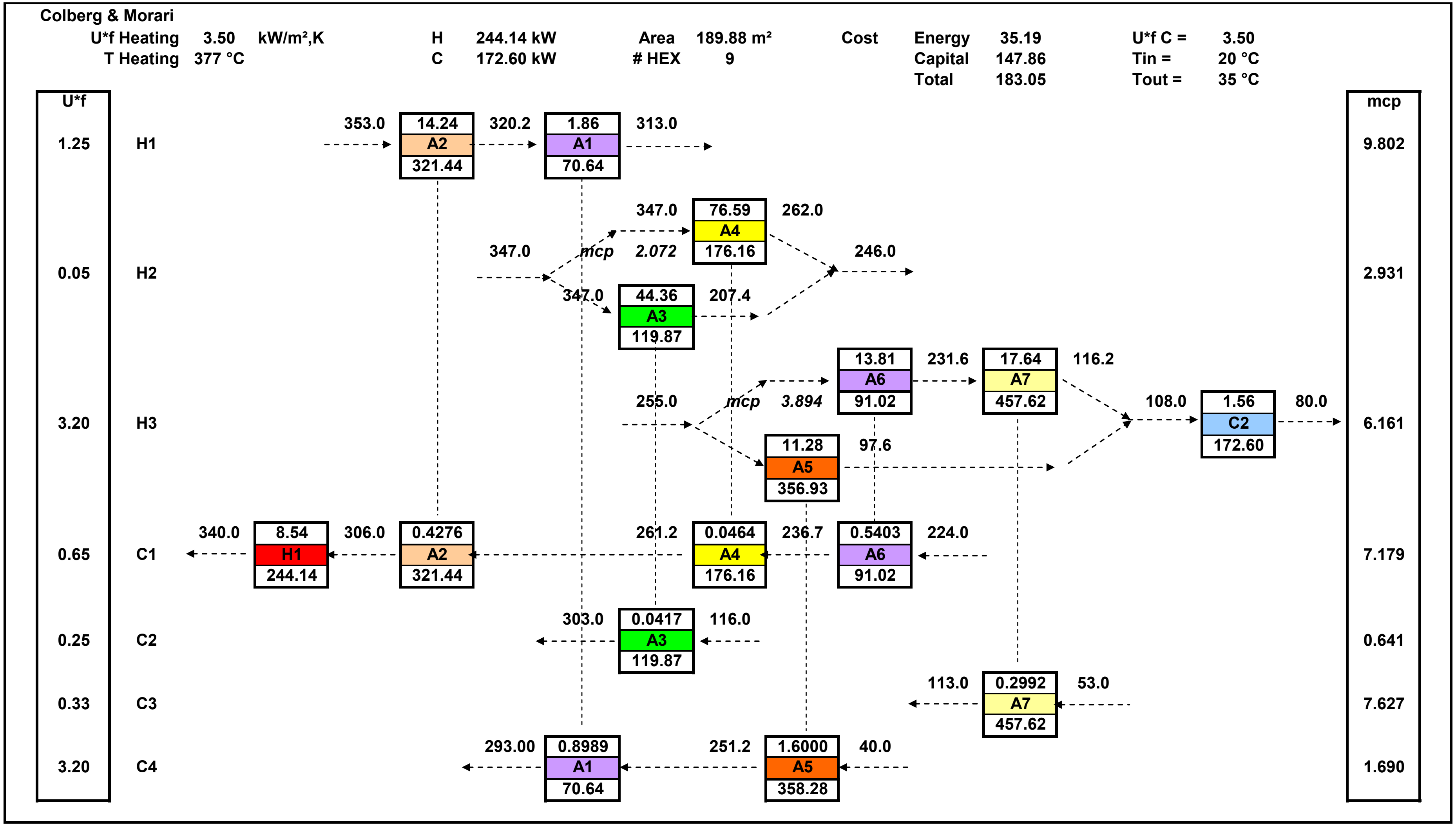

Colberg & Morari
U*f Heating 3.50 kW/m²,K
T Heating 377 °C
H 244.14 kW
C 172.60 kW
Area 189.88 m²
HEX 9
Cost
Energy 35.19
Capital 147.86
Total 183.05
U*f C = 3.50
Tin = 20 °C
Tout = 35 °C
U*f
1.25
0.05
3.20
0.65
0.25
0.33
3.20
H1
H2
H3
C1
C2
C3
C4
mcp
9.802
2.931
6.161
7.179
0.641
7.627
1.690
353.0
14.24
A2
321.44
320.2
1.86
A1
70.64
313.0
347.0
76.59
A4
176.16
262.0
347.0
mcp
2.072
246.0
347.0
44.36
A3
119.87
207.4
13.81
A6
91.02
231.6
17.64
A7
457.62
116.2
255.0
mcp
3.894
108.0
1.56
C2
172.60
80.0
11.28
A5
356.93
97.6
340.0
8.54
H1
244.14
306.0
0.4276
A2
321.44
261.2
0.0464
A4
176.16
236.7
0.5403
A6
91.02
224.0
303.0
0.0417
A3
119.87
116.0
113.0
0.2992
A7
457.62
53.0
293.00
0.8989
A1
70.64
251.2
1.6000
A5
358.28
40.0

Fig.3.7

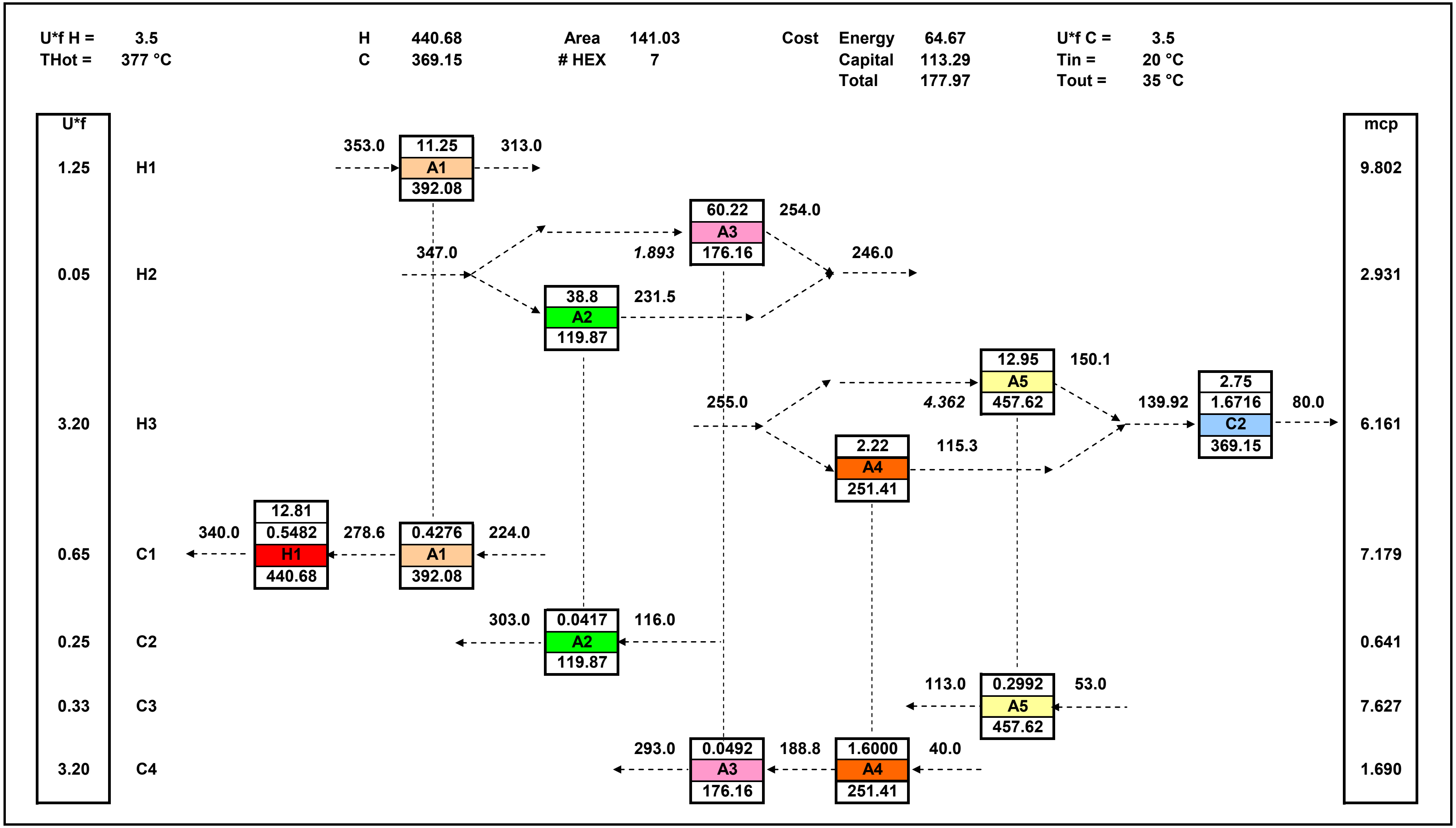

U*f H = 3.5
THot = 377 °C
H 440.68
C 369.15
Area 141.03
HEX 7
Cost Energy 64.67
Capital 113.29
Total 177.97
U*f C = 3.5
Tin = 20 °C
Tout = 35 °C
U*f
mcp
1.25 H1 9.802
0.05 H2 2.931
3.20 H3 6.161
0.65 C1 7.179
0.25 C2 0.641
0.33 C3 7.627
3.20 C4 1.690
353.0
11.25
A1
392.08
313.0
60.22
A3
176.16
254.0
347.0
1.893
246.0
38.8
A2
119.87
231.5
12.95
A5
457.62
150.1
255.0
4.362
139.92
2.75
1.6716
C2
369.15
80.0
2.22
A4
251.41
115.3
12.81
0.5482
H1
440.68
340.0
278.6
0.4276
A1
392.08
224.0
303.0
0.0417
A2
119.87
116.0
113.0
0.2992
A5
457.62
53.0
293.0
0.0492
A3
176.16
188.8
1.6000
A4
251.41
40.0

Fig.3.8

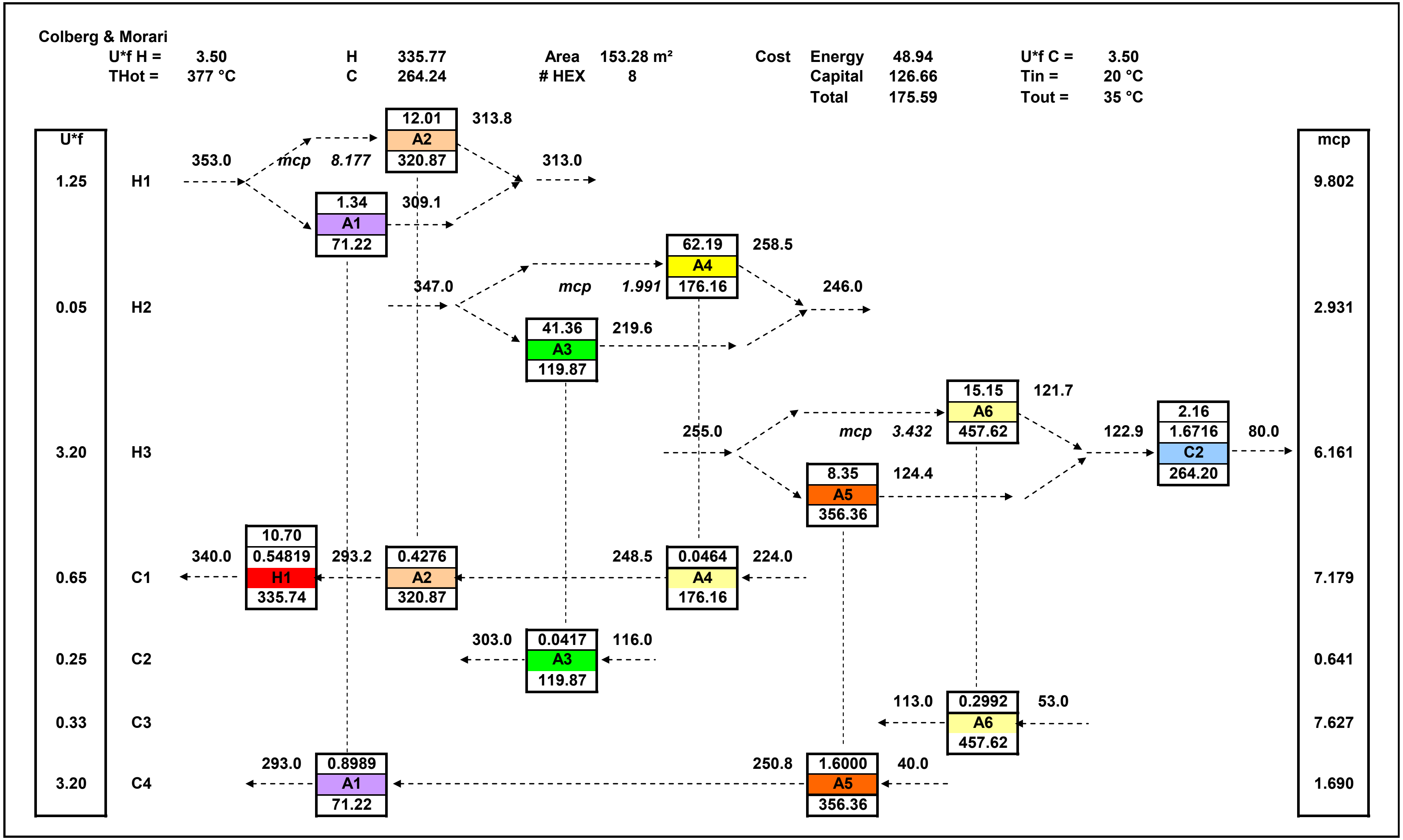

Colberg & Morari
U*f H = 3.50
THot = 377 °C
H 335.77
C 264.24
Area 153.28 m²
HEX 8
Cost
Energy 48.94
Capital 126.66
Total 175.59
U*f C = 3.50
Tin = 20 °C
Tout = 35 °C
U*f
1.25
0.05
3.20
0.65
0.25
0.33
3.20
H1
H2
H3
C1
C2
C3
C4
mcp
9.802
2.931
6.161
7.179
0.641
7.627
1.690
353.0
mcp 8.177
12.01
A2
320.87
313.8
313.0
1.34
A1
71.22
309.1
62.19
A4
176.16
258.5
347.0
mcp 1.991
246.0
41.36
A3
119.87
219.6
15.15
A6
457.62
121.7
255.0
mcp 3.432
122.9
2.16
1.6716
C2
264.20
80.0
8.35
A5
356.36
124.4
340.0
10.70
0.54819
H1
335.74
293.2
0.4276
A2
320.87
248.5
0.0464
A4
176.16
224.0
303.0
0.0417
A3
119.87
116.0
113.0
0.2992
A6
457.62
53.0
293.0
0.8989
A1
71.22
250.8
1.6000
A5
356.36
40.0

Fig.3.9