Heat exchanger network synthesis based on optimized input data sets
Pinch analysis with crisscross optimization prior to design
A new tick-off procedure for synthesis of networks without splits

Example Case 15 ï The 9SP Aromatics Plant revisited using an improved tick-off procedure

Author : Daniel Declercq **daniel.declercq@pinchco.com**

Keywords: pinch analysis, heat exchanger network synthesis, crisscross optimization

During the last four decades, numerous methods have been developed for synthesis of heat exchanger networks. From the mid-seventies on, mathematical programming using Transportation and Transhipment models were proposed for the synthesis task and significant progress has been made in view of automating the design work. Intensive research is still continuing today with the aim to producing models for practical use and procedures that guarantee a result that is at least close to the economical optimum.

With the introduction of pinch analysis in the late seventies, a new systematic approach became available for analysis prior to design. With the tick-off and stream-splitting rules, a theoretically simple and straightforward procedure was presented for design of the heat exchanger network. Unfortunately, in practice, application of said rules often leads to complicated initial networks that are hard to develop into practical ones.

A new approach was now tested, based on the following procedural steps:

- A targeting stage using pinch analysis with crisscross optimisation prior to design
- Generation of the corresponding grid
- Simplification of the grid in order to reduce the number of vertical integration bands whilst staying close to the minimum area
- Design of an initial network without stream splits using smart tick-off procedure
- Evolution of the network using incremental optimisation
- Introduction of additional heaters or coolers if so appropriate to enhance network flexibility
- Distortion of the solution space to escape from topology traps (sub-optima)
- Inspection of the network in order to identify the units with highest specific cost as candidates for manual elimination.

Below are the results of the approach applied on the 9SP ñAromatics Plantò problem, which first was presented by Linnhoff and Ahmad in 1990. The case has been studied intensively by many researchers and can be seen as a benchmark case for heat exchanger network synthesis. It was also treated on the Pinchco.com website as Example Case 4.

The energy versus capital trade-off curves are shown in Figure15.1; the data for the crisscross optimisation alternative with optimised shift contributions are shown in Table 15.1

When applying classic pinch analysis, the energy versus capital trade-off will generate a cost minimum for a heating load of 24275 kW and a target area of 17664 m². With crisscross optimisation prior to design, the energy versus capital trade-off will generate a cost minimum for a heating load of 24085 kW and a target area of 17476 m².

Figure 15.1

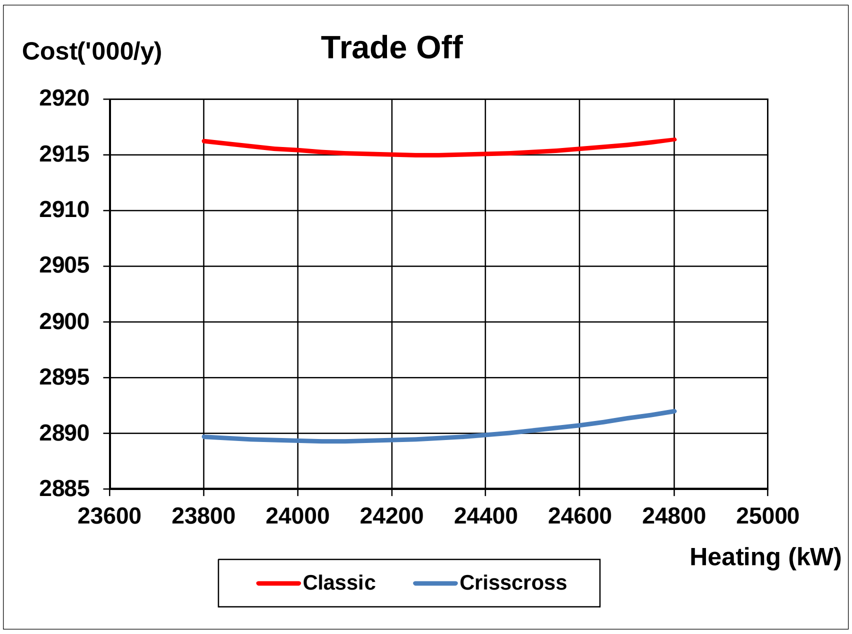

Table 15.1

Tsupply °C	Ttarget °C	Heat MW	DT-shift K	U*f kW/K,m²	Descript. -
327	40	28700	1	0.500	H1
220	160	9600	2	0.400	H2
220	60	9600	12	0.140	H3
160	45	46000	4	0.300	H4
100	300	20000	4	0.350	C1
35	164	9030	1	0.700	C2
85	138	18550	2	0.500	C3
60	170	6600	12	0.140	C4
140	300	32000	0	0.600	C5
330	250	24085	0	0.500	Heating
15	30	31805	0	0.500	Cooling

Heating	60/kW,year
Cooling	6/kW,year
Hex:	(2000 + 70 x Area)/year

The network is developed following pinch design rules. The pinch is caused by Cold stream C1 and the grid diagram is segregated at the pinch.

The middle section of the grid diagram is shown in Table 15.2. Below the pinch, stream matches can be placed following the tick-off procedure; there are no alternatives other than those shown in Figure 15.2.

Table 15.2

						Pinch		
		DeltaTS (K)	12.6	4.2	1.2	0.0	2.4	13.9
Stream	mcp	DeltaQ (kW)	10535	820	20060	8160	1950	2555
	kW/K	Band (N°)	8	9	10	11	12	13
H1	100	T (°C)	194.48	161.56	156.50	121.39	106.82	103.34
H2	160		195.48	162.56	160.00			
H3	60		205.98	173.06	168.00	132.89	118.32	114.84
H4	400				160.00	124.89	110.32	106.84
C1	100		160.50	136.00	133.90	100.00		
C2	70		164.00	139.50	137.40	103.50	86.50	71.50
C3	350			138.00	135.90	102.00	85.00	
C4	60		152.50	128.00	125.90	92.00	75.00	60.00
C5	200		164.50	140.00				

Above the pinch, hot steam H4 would have to be split in order to respect mcp rules. However, in order to avoid stream splitting, the problem will be solved starting from the next pinch, caused by hot stream H4 and shown as PINCH 2 in Figure 15.2; stream splitting is no longer required now to satisfy mcp rules and placing matches in the intermediate section.

When applying the new procedure, whilst some matches in the intermediate section are mandatory, others are not and several alternatives can be worked out. Further development on the hot side of PINCH 2 also leaves a number of choices for setting up initial networks. Different initial networks will have different cost and the preferred sequence may change after incremental evolution as shown in Table 15.3.

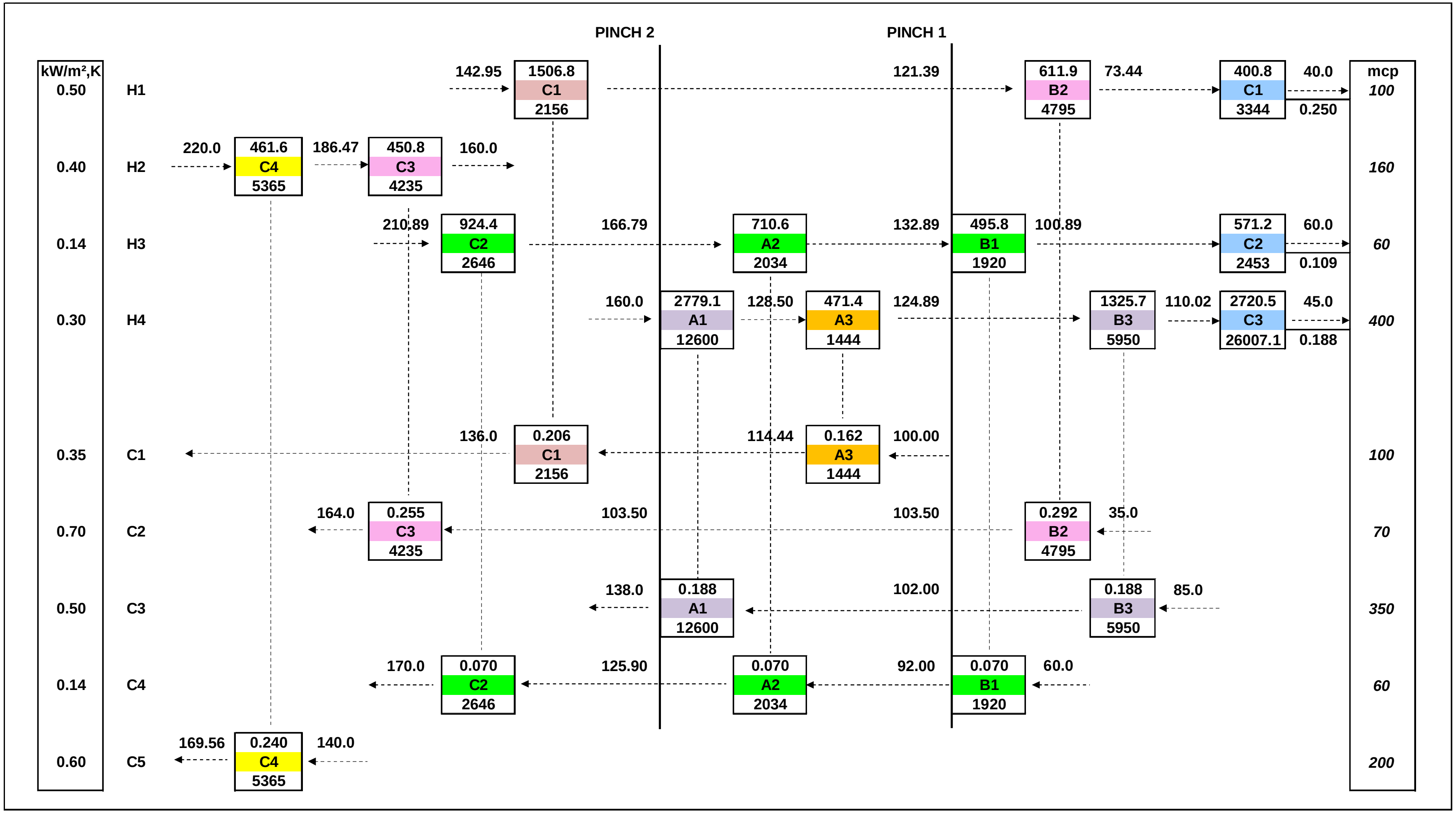
PINCH 2
PINCH 1
kW/m²,K
0.50
H1
142.95
1506.8
C1
2156
121.39
611.9
B2
4795
73.44
400.8
C1
3344
40.0
0.250
mcp
100
0.40
H2
220.0
461.6
C4
5365
186.47
450.8
C3
4235
160.0
160
0.14
H3
210.89
924.4
C2
2646
166.79
710.6
A2
2034
132.89
495.8
B1
1920
100.89
571.2
C2
2453
60.0
0.109
60
0.30
H4
160.0
2779.1
A1
12600
128.50
471.4
A3
1444
124.89
1325.7
B3
5950
110.02
2720.5
C3
26007.1
45.0
0.188
400
0.35
C1
136.0
0.206
C1
2156
114.44
0.162
A3
1444
100.00
100
0.70
C2
164.0
0.255
C3
4235
103.50
103.50
0.292
B2
4795
35.0
70
0.50
C3
138.0
0.188
A1
12600
102.00
0.188
B3
5950
85.0
350
0.14
C4
170.0
0.070
C2
2646
125.90
0.070
A2
2034
92.00
0.070
B1
1920
60.0
60
0.60
C5
169.56
0.240
C4
5365
140.0
200

Figure 15.2

Table 15.3

	Number	Heating MW	Area m²	Cost '000	# units
Initial networks					
	1	24.085	17901	2919.03	15
	2	24.085	17878	2919.39	16
	3	24.085	17971	2923.92	15
	4	24.085	18130	2935.02	15
	5	24.085	18344	2951.99	16
	6	24.085	18424	2955.58	15
	7	24.085	18515	2962.01	15
After incremental evolution					
	6	24.023	17628	2895.77	15
	3	24.186	17518	2896.86	14
	7	24.088	17589	2897.37	15
	1	23.991	17690	2898.00	15
	4	24.598	17132	2899.03	15
	5	24.442	17252	2899.14	16
	2	23.934	17737	2899.54	16

Further development of the initial networks leads to a long list of final networks, part of the results of which is shown in Table 15.4, together with the results of published literature studies. In total, more than 60 networks were developed with a cost, lower than the lowest figure published. For each number of units, the improvement vis-à-vis published results is significant.

The best network has 14 units and a cost of 2895.63 K. The lowest cost network with stream splits developed so far has a cost of 2888.78 K, has 16 units and 7 splits (see Case 4 on the Pinchco.com website).

The lowest cost network with stream splits reported in literature has a cost of 2904.3 K and 2 splits (Avila-Diaz, 2008); that cost would go down to 2902.70 if non-isothermal splits were applied; the list below reports 10 networks without stream split at a lower cost.

The most attractive networks for a number of units from 16 down to 10 are shown in the Figures 15.3 to 15.9.

Attractive networks without steam split can also be ñre-engineeredòinto networks with split such as the example in Figure 15.10, derived from Figure 15.5, leading to a new network with 13 units and 1 split at a cost of 2893.39 K.

The new procedure enabled the development of a very large number of networks not found by other methods.

It is frequently argued that mathematical methods need no optimised initial configuration to start with. This study shows that an optimised data set from the analysis can be very beneficial for synthesising an initial design with good potential for further improvement. Some initial networks in Table 15.3 are already better than many examples from literature.

Table 15.4

Example 9SP	QHot(MW)	Area (m²)	Cost ('000)	# HEX	vs best
Published Networks without Splits					
Zhu (1995)	26.83	16390	2984.42	10	
Chakraborty &Ghosh (1999)	25.90	17029	2971.75	12	
Bogataj (2012-corrected)	23.63	18816	2951.04	14	
Lewin (1998)	25.69	16880	2946.00	11	
Yerramsetty & Murty (2008)	25.88	16536	2942.00	15	
Peng (2015)	24.50	17799	2942.00	14	
Peng (2015)	24.50	17745	2935.12	15	
Bergamini (2007)	23.60	18593	2935.02	15	
This research	**24.46**	**17218**	**2897.72**	**16**	**-**
	24.44	17252	2899.14	16	
	23.93	17737	2899.54	16	
	24.09	18344	2951.99	16	
	24.02	**17628**	**2895.77**	**15**	**-1.3%**
	24.09	17589	2897.37	15	
	24.57	17144	2897.77	15	
	24.54	17170	2897.81	15	
	23.99	17690	2898.00	15	
	24.21	**17483**	**2895.63**	**14**	**-1.6%**
	24.19	17518	2896.86	14	
	23.98	17814	2903.96	14	
	24.69	17169	2905.57	14	
	24.56	17301	2906.35	14	
	24.17	**17644**	**2902.82**	**13**	**-**
	24.59	17322	2907.59	13	
	24.44	17531	2912.54	13	
	24.12	17845	2913.55	13	
	25.81	16262	2914.19	13	
	24.30	**17703**	**2913.47**	**12**	**-2.0%**
	24.68	17395	2916.81	12	
	25.74	16482	2922.90	12	
	23.48	18636	2924.31	12	
	24.53	17648	2924.79	12	
	26.15	**16160**	**2925.47**	**11**	**-0.7%**
	26.14	16174	2925.68	11	
	26.13	16314	2935.09	11	
	23.88	18447	2935.38	11	
	24.92	17472	2936.21	11	
	25.75	**16904**	**2948.76**	**10**	**-1.2%**
	25.68	17202	2965.60	10	

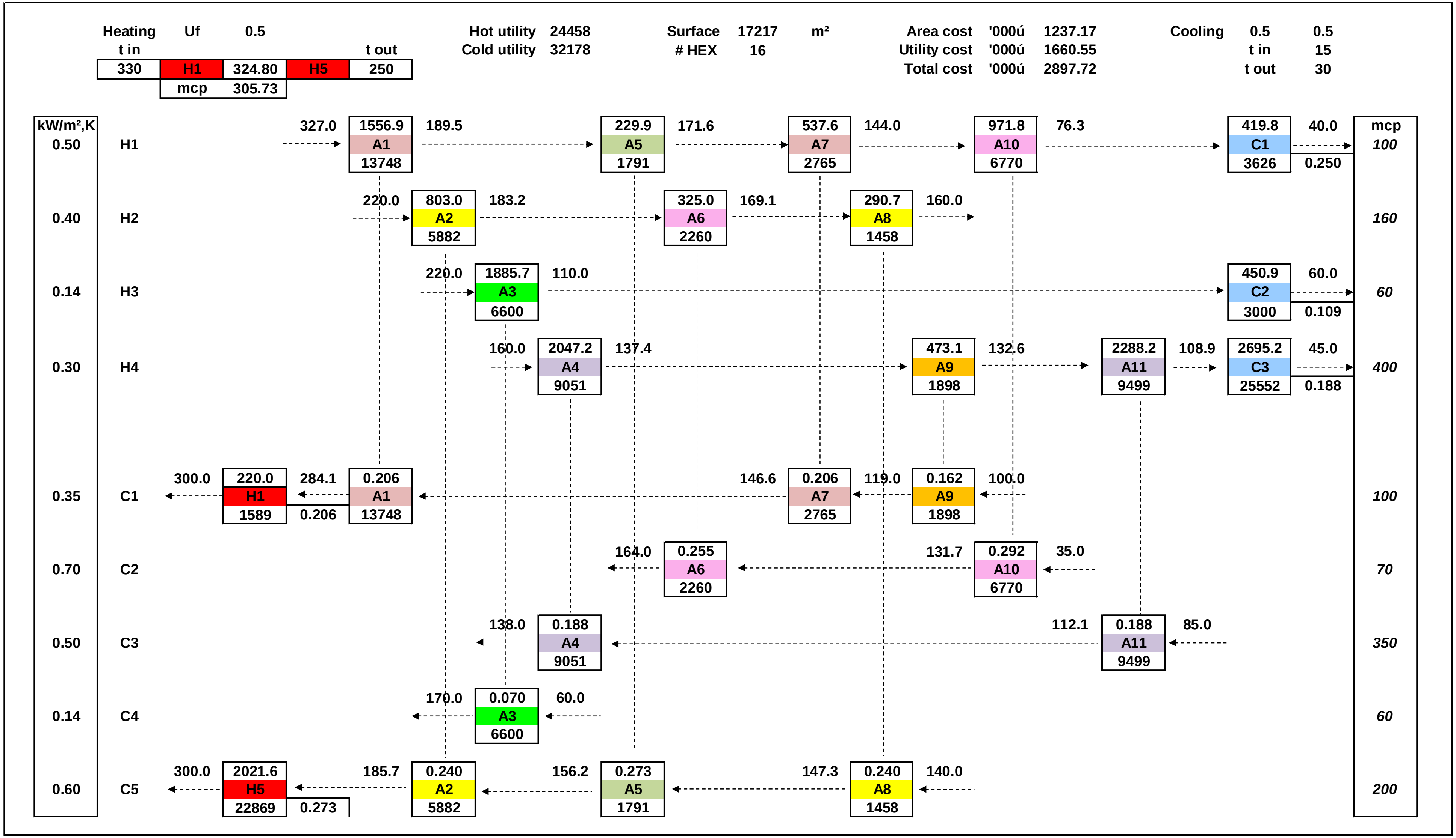
Heating
Uf
0.5
t in
t out
330
H1
324.80
H5
250
mcp
305.73
Hot utility
24458
Cold utility
32178
Surface
17217
m²
HEX
16
Area cost
'000ú
1237.17
Utility cost
'000ú
1660.55
Total cost
'000ú
2897.72
Cooling
0.5
0.5
t in
15
t out
30
kW/m²,K
mcp
0.50
H1
100
0.40
H2
160
0.14
H3
60
0.30
H4
400
0.35
C1
100
0.70
C2
70
0.50
C3
350
0.14
C4
60
0.60
C5
200
327.0
1556.9
A1
13748
189.5
229.9
A5
1791
171.6
537.6
A7
2765
144.0
971.8
A10
6770
76.3
419.8
C1
3626
40.0
0.250
220.0
803.0
A2
5882
183.2
325.0
A6
2260
169.1
290.7
A8
1458
160.0
220.0
1885.7
A3
6600
110.0
450.9
C2
3000
60.0
0.109
160.0
2047.2
A4
9051
137.4
473.1
A9
1898
132.6
2288.2
A11
9499
108.9
2695.2
C3
25552
45.0
0.188
300.0
220.0
H1
1589
284.1
0.206
0.206
A1
13748
146.6
0.206
A7
2765
119.0
0.162
A9
1898
100.0
164.0
0.255
A6
2260
131.7
0.292
A10
6770
35.0
138.0
0.188
A4
9051
112.1
0.188
A11
9499
85.0
170.0
0.070
A3
6600
60.0
300.0
2021.6
H5
22869
0.273
185.7
0.240
A2
5882
156.2
0.273
A5
1791
147.3
0.240
A8
1458
140.0

Figure 15.3

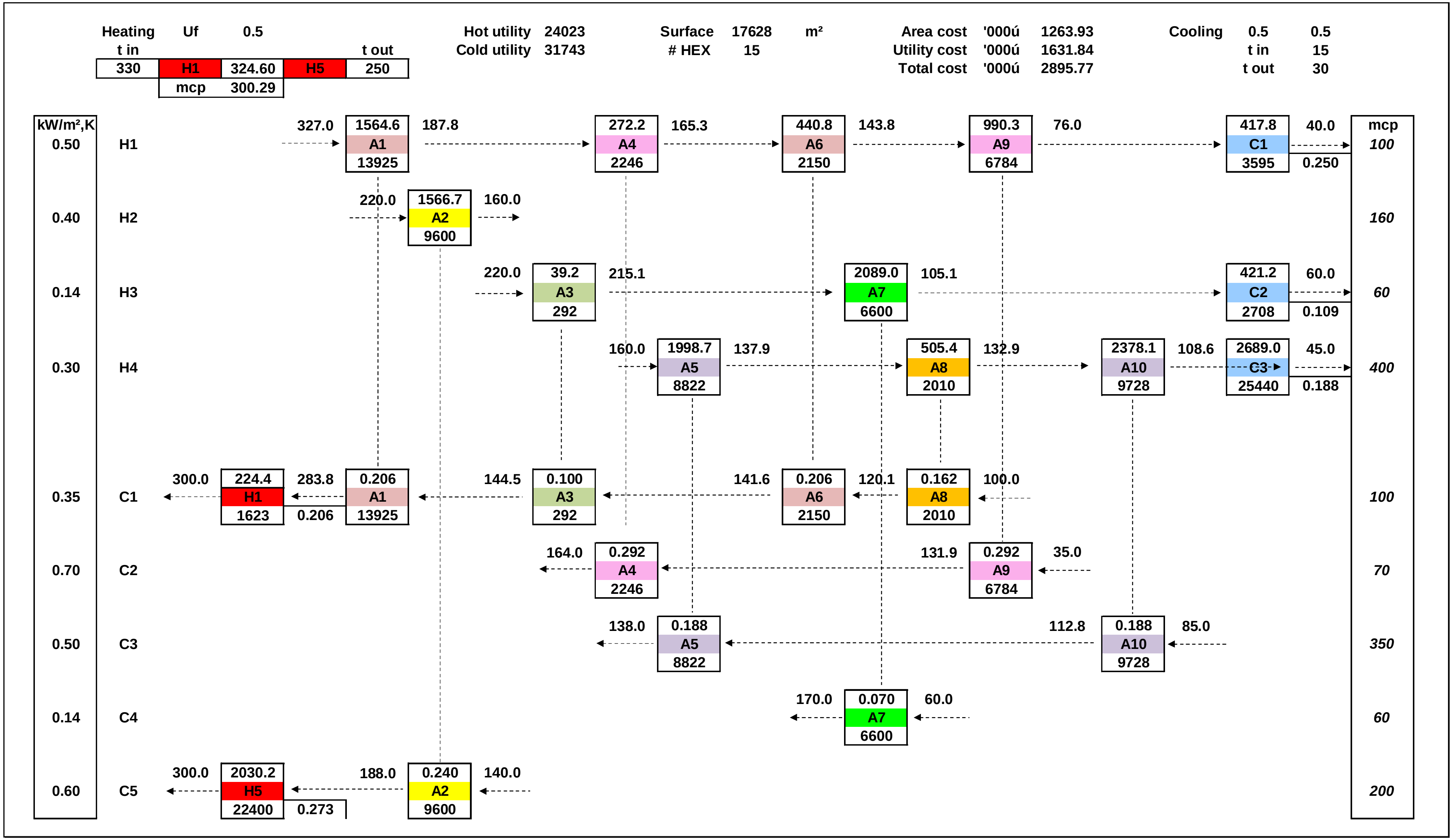
Heating
Uf
0.5
t in
t out
330
H1
324.60
H5
250
mcp
300.29
Hot utility
24023
Cold utility
31743
Surface
17628
m²
HEX
15
Area cost
'000ú
1263.93
Utility cost
'000ú
1631.84
Total cost
'000ú
2895.77
Cooling
0.5
0.5
t in
15
t out
30
kW/m²,K
mcp
0.50
H1
327.0
1564.6
A1
13925
187.8
272.2
A4
2246
165.3
440.8
A6
2150
143.8
990.3
A9
6784
76.0
417.8
C1
3595
40.0
0.250
100
0.40
H2
220.0
1566.7
A2
9600
160.0
160
0.14
H3
220.0
39.2
A3
292
215.1
2089.0
A7
6600
105.1
421.2
C2
2708
60.0
0.109
60
0.30
H4
160.0
1998.7
A5
8822
137.9
505.4
A8
2010
132.9
2378.1
A10
9728
108.6
2689.0
C3
25440
45.0
0.188
400
0.35
C1
300.0
224.4
H1
1623
283.8
0.206
0.206
A1
13925
144.5
0.100
A3
292
141.6
0.206
A6
2150
120.1
0.162
A8
2010
100.0
100
0.70
C2
164.0
0.292
A4
2246
131.9
0.292
A9
6784
35.0
70
0.50
C3
138.0
0.188
A5
8822
112.8
0.188
A10
9728
85.0
350
0.14
C4
170.0
0.070
A7
6600
60.0
60
0.60
C5
300.0
2030.2
H5
22400
0.273
188.0
0.240
A2
9600
140.0
200

Figure 15.4

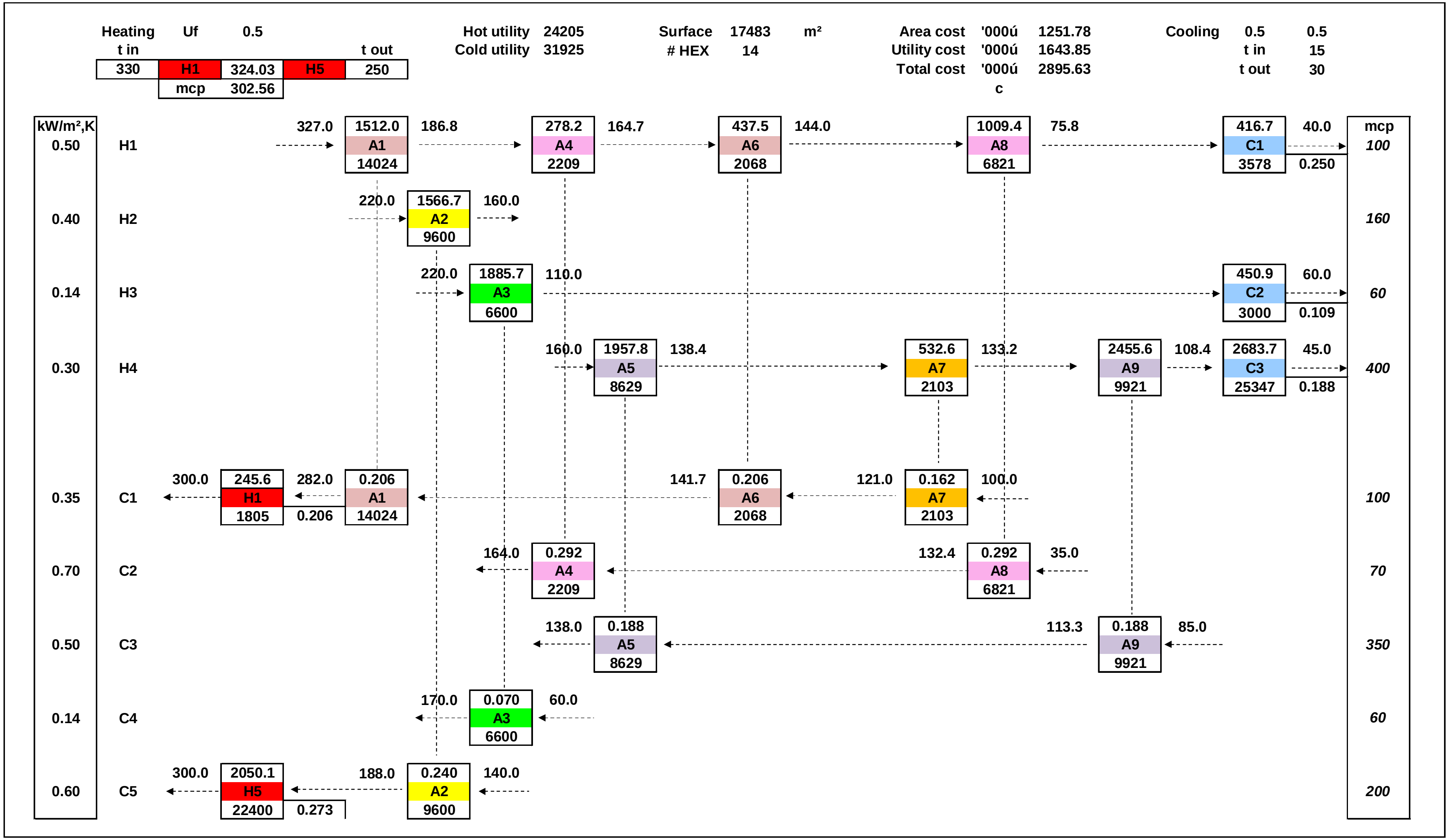
Heating
Uf
0.5
t in
t out
330
H1
324.03
H5
250
mcp
302.56
Hot utility
24205
Cold utility
31925
Surface
17483
m²
HEX
14
Area cost
'000ú
1251.78
Utility cost
'000ú
1643.85
Total cost
'000ú
2895.63
c
Cooling
0.5
0.5
t in
15
t out
30
kW/m²,K
mcp
0.50
H1
100
327.0
1512.0
A1
14024
186.8
278.2
A4
2209
164.7
437.5
A6
2068
144.0
1009.4
A8
6821
75.8
416.7
C1
3578
40.0
0.250
0.40
H2
160
220.0
1566.7
A2
9600
160.0
0.14
H3
60
220.0
1885.7
A3
6600
110.0
450.9
C2
3000
60.0
0.109
0.30
H4
400
160.0
1957.8
A5
8629
138.4
532.6
A7
2103
133.2
2455.6
A9
9921
108.4
2683.7
C3
25347
45.0
0.188
0.35
C1
100
300.0
245.6
H1
1805
282.0
0.206
0.206
A1
14024
141.7
0.206
A6
2068
121.0
0.162
A7
2103
100.0
0.70
C2
70
164.0
0.292
A4
2209
132.4
0.292
A8
6821
35.0
0.50
C3
350
138.0
0.188
A5
8629
113.3
0.188
A9
9921
85.0
0.14
C4
60
170.0
0.070
A3
6600
60.0
0.60
C5
200
300.0
2050.1
H5
22400
0.273
188.0
0.240
A2
9600
140.0

Figure 15.5

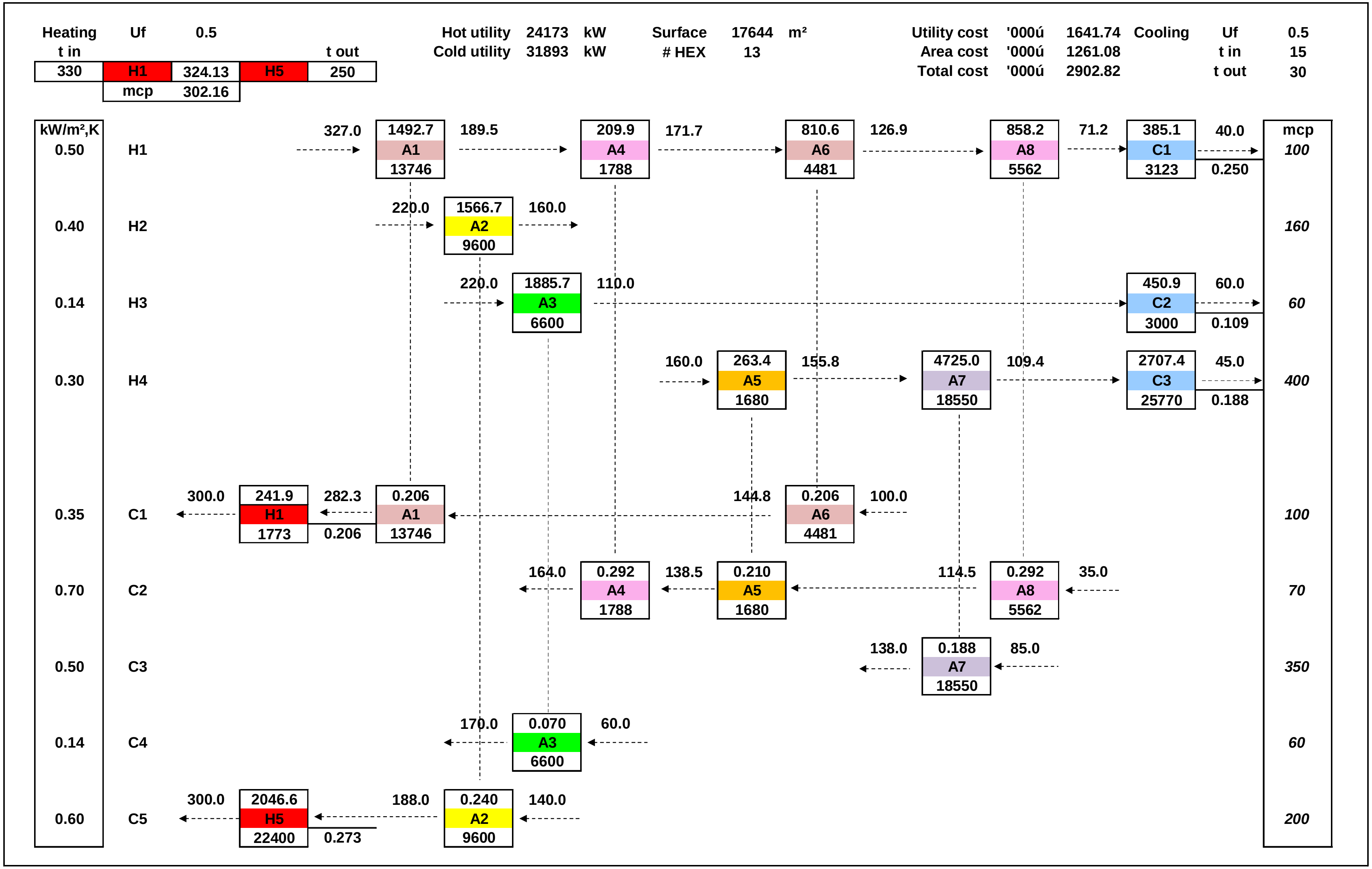
Heating
Uf
0.5
t in
330
H1
324.13
H5
t out
250
mcp
302.16
Hot utility
24173
kW
Cold utility
31893
kW
Surface
17644
m²
HEX
13
Utility cost
'000ú
1641.74
Area cost
'000ú
1261.08
Total cost
'000ú
2902.82
Cooling
Uf
0.5
t in
15
t out
30
kW/m²,K
mcp
0.50
H1
100
0.40
H2
160
0.14
H3
60
0.30
H4
400
0.35
C1
100
0.70
C2
70
0.50
C3
350
0.14
C4
60
0.60
C5
200
327.0
1492.7
A1
13746
189.5
209.9
A4
1788
171.7
810.6
A6
4481
126.9
858.2
A8
5562
71.2
385.1
C1
3123
40.0
0.250
220.0
1566.7
A2
9600
160.0
220.0
1885.7
A3
6600
110.0
450.9
C2
3000
60.0
0.109
160.0
263.4
A5
1680
155.8
4725.0
A7
18550
109.4
2707.4
C3
25770
45.0
0.188
300.0
241.9
H1
1773
282.3
0.206
0.206
A1
13746
144.8
0.206
A6
4481
100.0
164.0
0.292
A4
1788
138.5
0.210
A5
1680
114.5
0.292
A8
5562
35.0
138.0
0.188
A7
18550
85.0
170.0
0.070
A3
6600
60.0
300.0
2046.6
H5
22400
0.273
188.0
0.240
A2
9600
140.0

Figure 15.6

]

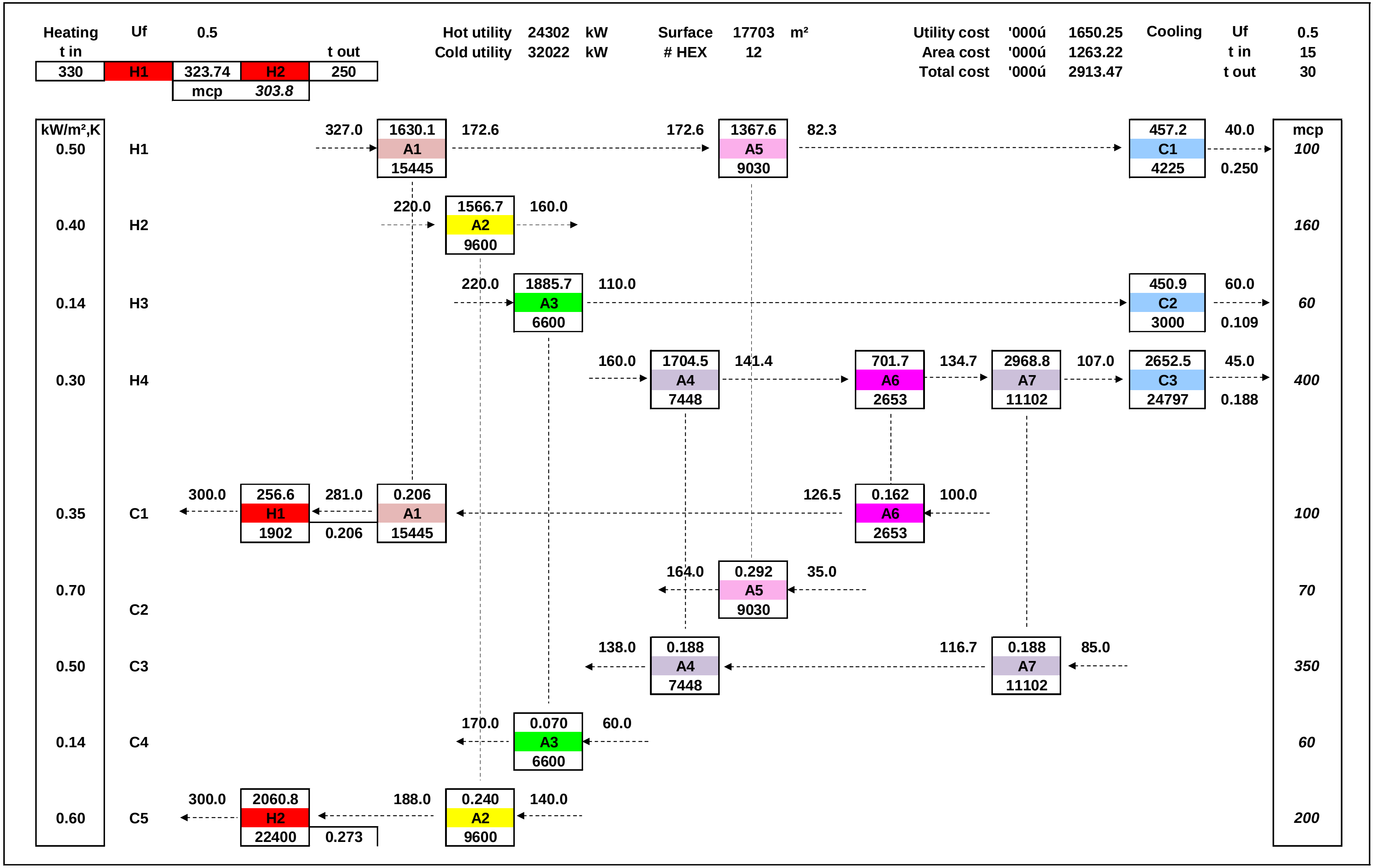
Heating
Uf
0.5
t in
t out
330
H1
323.74
H2
250
mcp
303.8
Hot utility
24302
kW
Cold utility
32022
kW
Surface
17703
m²
HEX
12
Utility cost
'000ú
1650.25
Area cost
'000ú
1263.22
Total cost
'000ú
2913.47
Cooling
Uf
0.5
t in
15
t out
30
kW/m²,K
mcp
0.50
H1
327.0
1630.1
A1
15445
172.6
172.6
1367.6
A5
9030
82.3
457.2
C1
4225
40.0
0.250
100
0.40
H2
220.0
1566.7
A2
9600
160.0
160
0.14
H3
220.0
1885.7
A3
6600
110.0
450.9
C2
3000
60.0
0.109
60
0.30
H4
160.0
1704.5
A4
7448
141.4
701.7
A6
2653
134.7
2968.8
A7
11102
107.0
2652.5
C3
24797
45.0
0.188
400
0.35
C1
300.0
256.6
H1
1902
281.0
0.206
0.206
A1
15445
126.5
0.162
A6
2653
100.0
100
0.70
C2
164.0
0.292
A5
9030
35.0
70
0.50
C3
138.0
0.188
A4
7448
116.7
0.188
A7
11102
85.0
350
0.14
C4
170.0
0.070
A3
6600
60.0
60
0.60
C5
300.0
2060.8
H2
22400
0.273
188.0
0.240
A2
9600
140.0
200

Figure 15.7

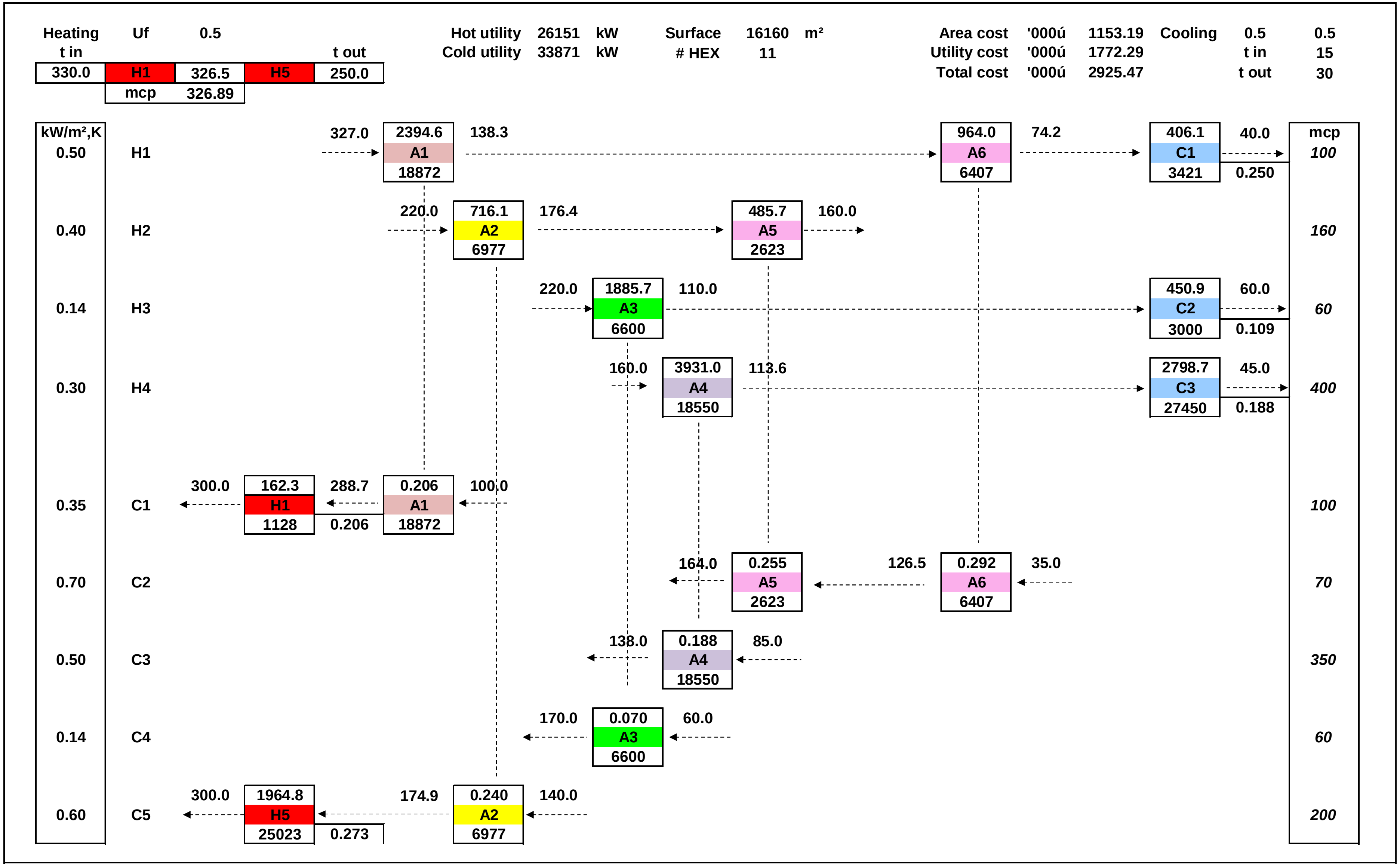
Heating
Uf
0.5
t in
330.0
H1
326.5
H5
t out
250.0
mcp
326.89
Hot utility
26151
kW
Cold utility
33871
kW
Surface
16160
m²
HEX
11
Area cost
'000ú
1153.19
Utility cost
'000ú
1772.29
Total cost
'000ú
2925.47
Cooling
0.5
0.5
t in
15
t out
30
kW/m²,K
0.50
H1
0.40
H2
0.14
H3
0.30
H4
0.35
C1
0.70
C2
0.50
C3
0.14
C4
0.60
C5
327.0
2394.6
A1
18872
138.3
964.0
A6
6407
74.2
406.1
C1
3421
40.0
0.250
mcp
100
220.0
716.1
A2
6977
176.4
485.7
A5
2623
160.0
160
220.0
1885.7
A3
6600
110.0
450.9
C2
3000
60.0
0.109
60
160.0
3931.0
A4
18550
113.6
2798.7
C3
27450
45.0
0.188
400
300.0
162.3
H1
1128
288.7
0.206
0.206
A1
18872
100.0
100
164.0
0.255
A5
2623
126.5
0.292
A6
6407
35.0
70
138.0
0.188
A4
18550
85.0
350
170.0
0.070
A3
6600
60.0
60
300.0
1964.8
H5
25023
0.273
174.9
0.240
A2
6977
140.0
200

Figure 15.8

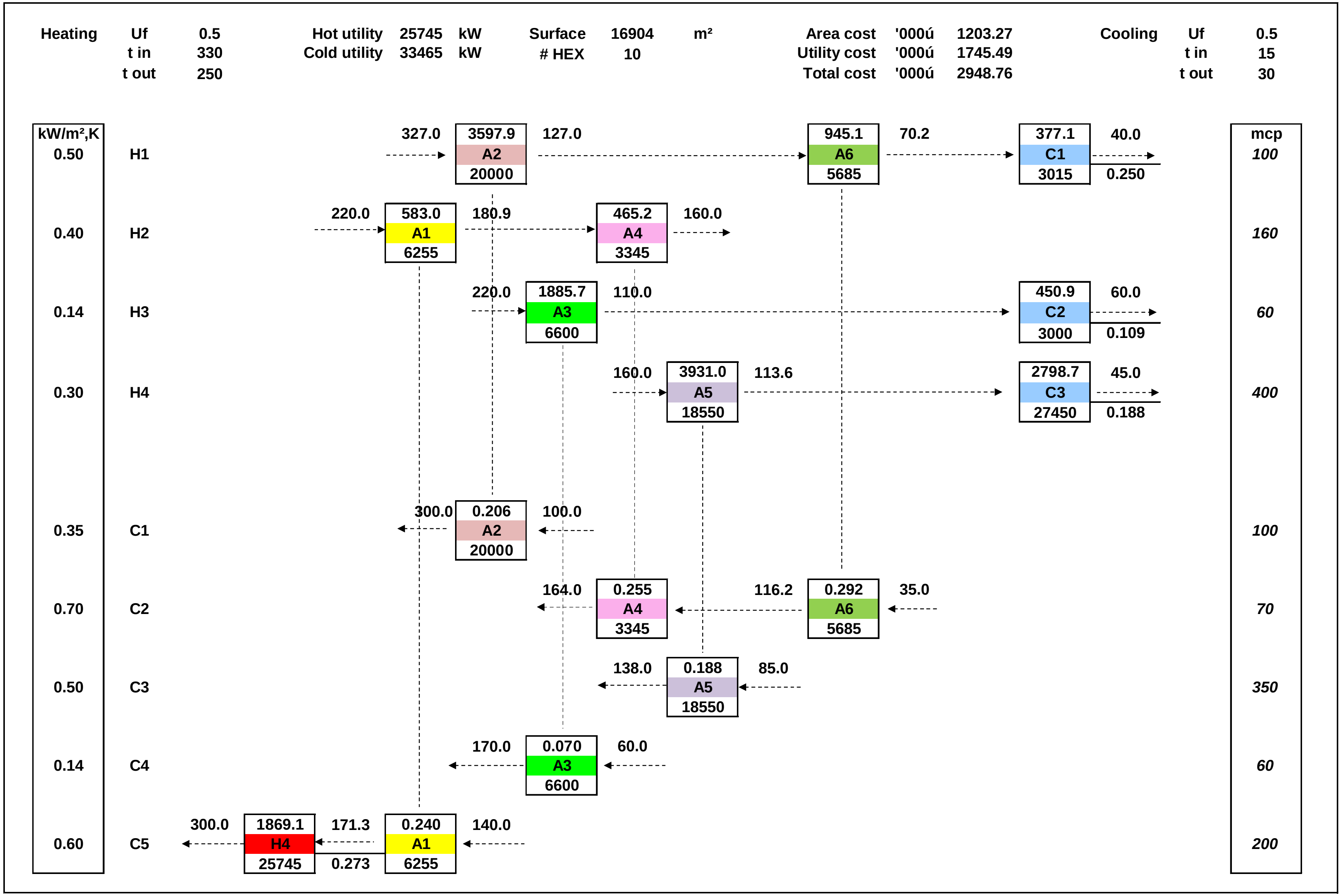
Heating
Uf 0.5
t in 330
t out 250
Hot utility 25745 kW
Cold utility 33465 kW
Surface 16904 m²
HEX 10
Area cost '000ú 1203.27
Utility cost '000ú 1745.49
Total cost '000ú 2948.76
Cooling
Uf 0.5
t in 15
t out 30
kW/m²,K
mcp
0.50 H1 100
0.40 H2 160
0.14 H3 60
0.30 H4 400
0.35 C1 100
0.70 C2 70
0.50 C3 350
0.14 C4 60
0.60 C5 200
327.0
3597.9
A2
20000
127.0
945.1
A6
5685
70.2
377.1
C1
3015
40.0
0.250
220.0
583.0
A1
6255
180.9
465.2
A4
3345
160.0
220.0
1885.7
A3
6600
110.0
450.9
C2
3000
60.0
0.109
160.0
3931.0
A5
18550
113.6
2798.7
C3
27450
45.0
0.188
300.0
0.206
A2
20000
100.0
164.0
0.255
A4
3345
116.2
0.292
A6
5685
35.0
138.0
0.188
A5
18550
85.0
170.0
0.070
A3
6600
60.0
300.0
1869.1
H4
25745
171.3
0.273
0.240
A1
6255
140.0

Figure 15.9

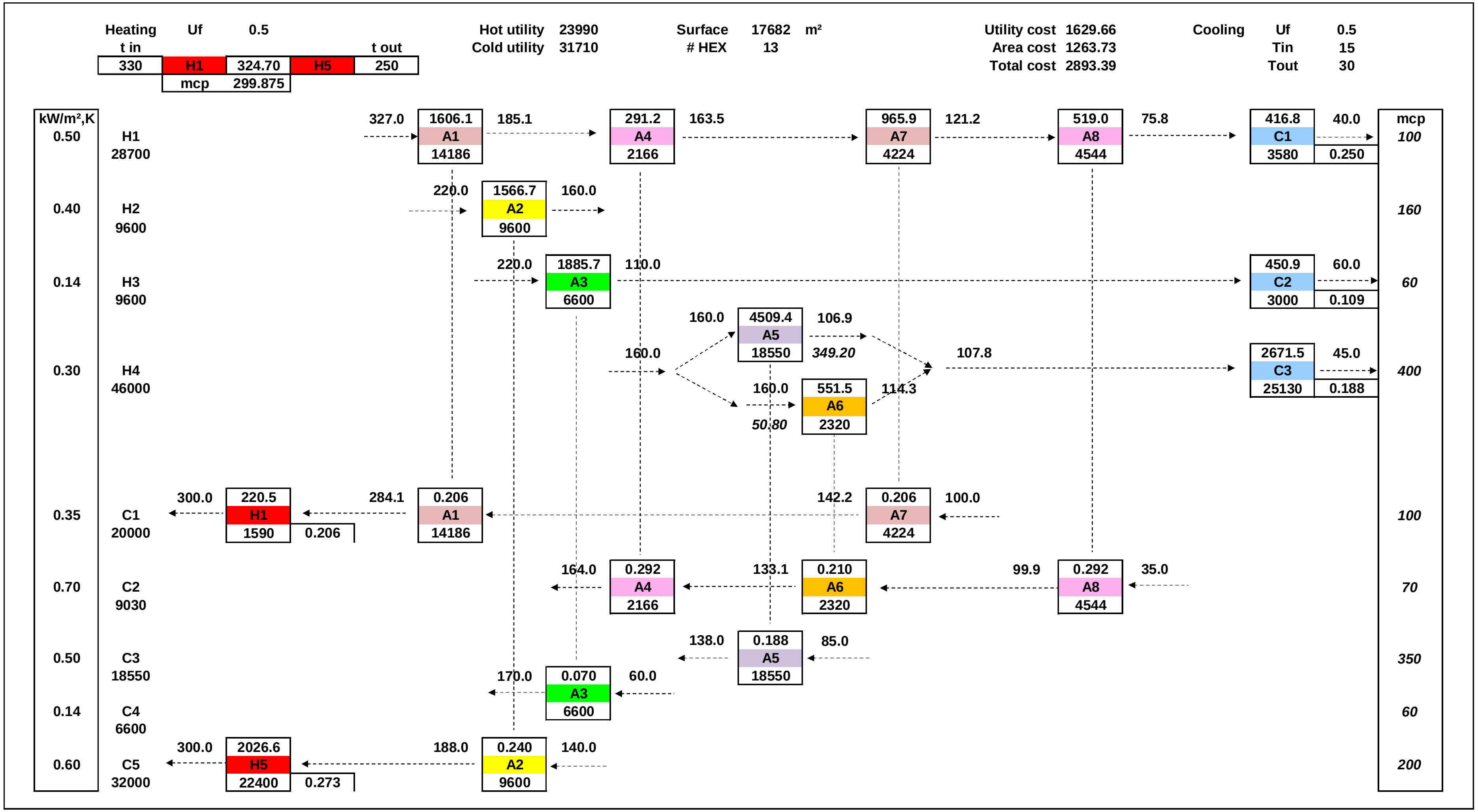
Heating
Uf
0.5
t in
330
H1
324.70
H5
t out
250
mcp
299.875
Hot utility
23990
Cold utility
31710
Surface
17682
m²
HEX
13
Utility cost
1629.66
Area cost
1263.73
Total cost
2893.39
Cooling
Uf
0.5
Tin
15
Tout
30
kW/m²,K
0.50
H1
28700
327.0
1606.1
A1
14186
185.1
291.2
A4
2166
163.5
965.9
A7
4224
121.2
519.0
A8
4544
75.8
416.8
C1
3580
40.0
0.250
mcp
100
0.40
H2
9600
220.0
1566.7
A2
9600
160.0
160
0.14
H3
9600
220.0
1885.7
A3
6600
110.0
450.9
C2
3000
60.0
0.109
60
160.0
4509.4
A5
18550
106.9
349.20
0.30
H4
46000
160.0
107.8
2671.5
C3
25130
45.0
0.188
400
160.0
551.5
A6
2320
114.3
50.80
0.35
C1
20000
300.0
220.5
H1
1590
0.206
284.1
0.206
A1
14186
142.2
0.206
A7
4224
100.0
100
0.70
C2
9030
164.0
0.292
A4
2166
133.1
0.210
A6
2320
99.9
0.292
A8
4544
35.0
70
0.50
C3
18550
138.0
0.188
A5
18550
85.0
350
170.0
0.070
A3
6600
60.0
0.14
C4
6600
60
0.60
C5
32000
300.0
2026.6
H5
22400
0.273
188.0
0.240
A2
9600
140.0
200

Figure 15.10