Heat Exchanger Networks, Benchmark Solutions for Literature Problems.

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This note is a summary of benchmark solutions for literature problems. A series of small networks with 2 hot streams and 2 cold streams has already been published on the Pinchco website [1].
The approach is based on simple procedures:

- Pinch analysis with, in case of unequal heat transfer coefficients, crisscross optimisation prior to design,
- Generation of the stream grid and transfer to an LP program for network synthesis,
- Simplification of the grid by reducing the number of integration bands (in the scientific literature known as "superstructures") and generation of an initial network,
- Elimination of the smallest heat exchanger units via loops between adjacent bands,
- Transfer of the results into a network optimisation program using incremental evolution and smart optimisation procedures, and heuristics to further reduce the annual cost by reducing the number of units and optimising the stream splits,
- Alternatively, network design following the tick-off procedure, combined with smart optimisation procedures and heuristics.

Smart optimisation procedures and heuristics have been explained on the Pinchco website [2].

Supporting software is written in Visual Basic for Excel.

Contents

1 Example from Adjiman.

Example 1 is from Adjiman et all. [3]. It has also been studied by Faria et al. [4], Lin et all. [5], Rezaei et all. [6], Aguitoni et all. [7], [8], Chang et al. [9] and Caballero et all. [10].

The data set is given in Table 1.1 hereunder.

Table 1.1

Tsupply	Ttarget	Heat	DT-Shift	U	Descript
K	K	kW	K	kW/K,m²	-
650	370	2800		1.000	H1
590	370	4400		1.000	H2
410	650	3600		1.000	C1
350	500	1950		1.000	C2
680	680	460		5.000	Heating
300	320	2110		1.000	Cooling

Cost data

Heating : 80 $ /kW,year Cooling : 15 $/kW,year

HEX cost : 5500 + 150 x Area $/year

Composite Curves are shown in Figure 1.1. Heating load in the table correspond with the heating load for minimum cost in the trade-off curves of Figure 1.2 in classic pinch analysis (2 systems with segregation at the pinch) as well as for a network with 1 system. The corresponding DTMin would be 10.66 K. Target cost for a network with 2 systems (pinch network with 6 units) is 151,073 $/year, respectively 145,573 $/year for a network with 1 system (5 units).

Design rules of pinch analysis will lead to a network with 6 units and an annual cost of 157,219 $, which after incremental evolution drops to 154,853 $ (Figure 1.3). Application of LP on the grid of the analysis (6 bands) generates a network with 11 units; this network is caught in a local optimum. Distortion of the solution space enables to get out of this suboptimum and the network evolves to the same network as with pinch design rules. Further distortion of the solution space leads to a network with 5 units and a cost of 154,431 $/year (Figure 1.4). Results can be compared in Table 1.2.

Table 1.2	Heating	Area	# of units	splits	Cost
	kW	m²	#	#	k$/year
Adjiman	460.0	356.95	6	0	154.993
Faria	491.1	336.71	6	0	154.911
Rezaei	500.0	342.34	6	0	154.997
Aguitoni [7]	479.3	343.79	6	0	154.853
Aguitoni [8]	523.6	349.60	5	0	154.432
Chang	490.6	337.02	6	0	154.911
Caballero *)	526.2	347.98	5	0	154.436
This study a	479.0	343.98	6	0	154.853
This study b	523.1	349.91	5	0	154.431

*) revised

The optimum results are the same as those obtained by Aguitoni, however, using much simpler procedures. The network of Caballero has the same structure as the optimum network, but a marginally higher heating load.

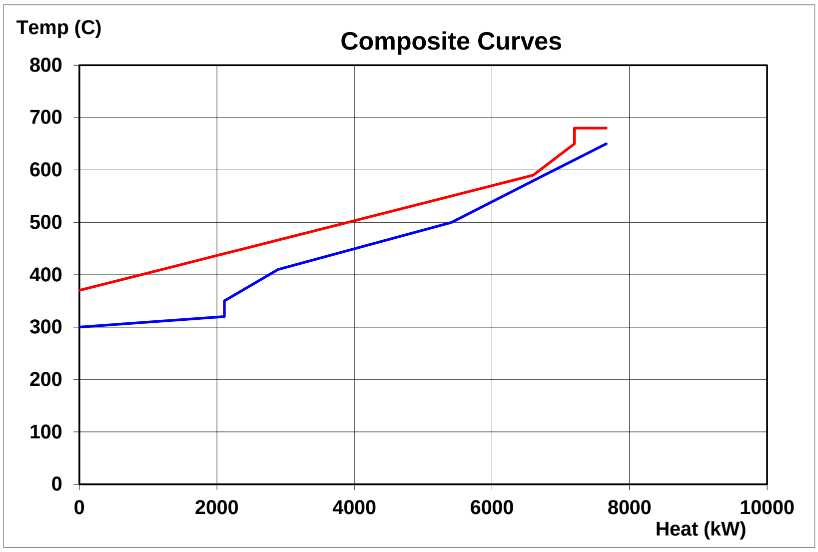


Figure 1.1

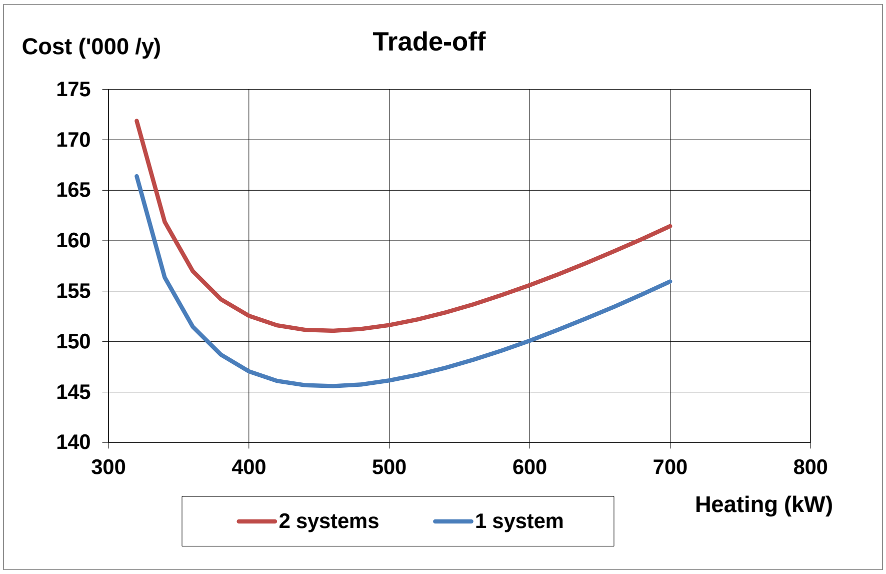


Figure 1.2

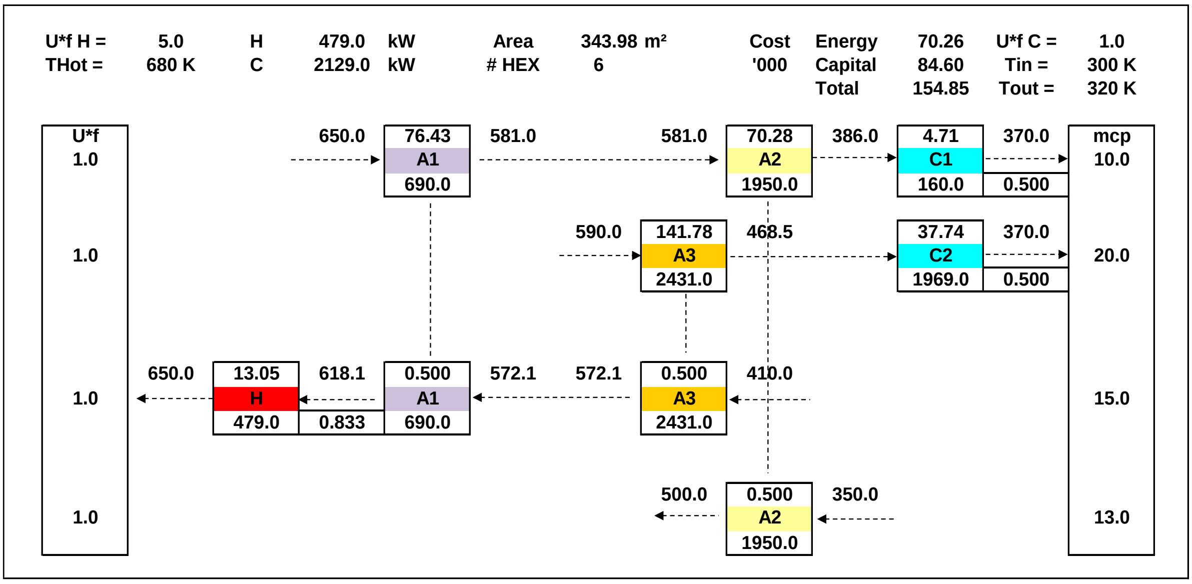


Figure 1.3

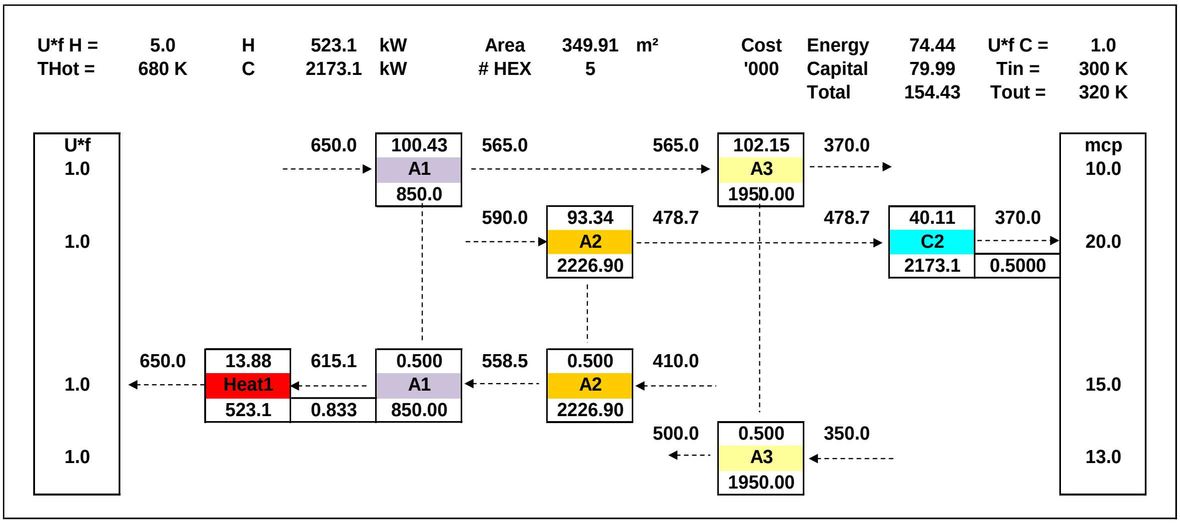


Figure 1.4

2 Example from Ahmad and from Gundersen & Grossmann

This example has been treated many times and is interesting for several reasons: the heat transfer coefficients of the various process streams are very unequal, the stream data structure has been explored with small heat loads, with mid-size heat loads and with large heat loads. This example problem was defined by Jegede et al. as one of the most difficult practical problems for targeting purposes [11].

2.1 The small-size problem

2.1.1 The original data set

This data set was treated in Suhail Ahmad [12], Xin X. Zhu [13] and [15] and X. X. Zhu et al. [14]. It was also studied by the author in [16].

Analysis was done with the original data set from Ahmad (Table 2.1).

Table 2.1

Tsupply	Ttarget	Heat	Shift	U	Description
°C	°C	kW	K	kW/m²,K	-
159	77	187.37	2.0	0.10	H1
267	80	38.15	13.0	0.04	H2
343	90	136.11	-6.0	0.50	H3
26	127	94.23	58.0	0.01	C1
118	265	288.27		0.50	C2
300	300	159.00	41.0	0.05	Heating
20	60	138.13		0.20	Cooling

Cost data

Heating : 110.0 EUR/kW,year   Cooling : 10.0 $/kW,year

Hex cost : 3800 + 750*Area$^{0.83}$ $

Life time: 6 years, interest 10%   Annuity: 22.96%

Annual Hex cost : 872.51 + 172.21*Area$^{0.83}$ $/year

Assuming steam for the hot utility, the temperature level would correspond with a saturation pressure of 85.9 bar, which would assume a steam distribution system at a pressure of 90 bar.

The shift values in Table 2.1 were obtained by crisscross optimisation prior to design; the heat load was chosen from the trade-off curve in Figure 2.1.

Results of the analysis can be compared in Table 2.2. The best network is shown in Figure 2.2.

Table 2.2	Heating	Area	units	splits	Cost
	kW	m²	#	#	'000 $/y
Ahmad	145.7	292.53	9	0	52.251
Zhu	169.2	242.30	6	2	46.552
This study	145.3	255.03	7	3	46.0672
	141.9	262.03	7	2	46.0675
	156.5	251.96	6	2	46.219
	144.3	280.69	7	1	46.275
	169.2	235.10	7	0	47.022

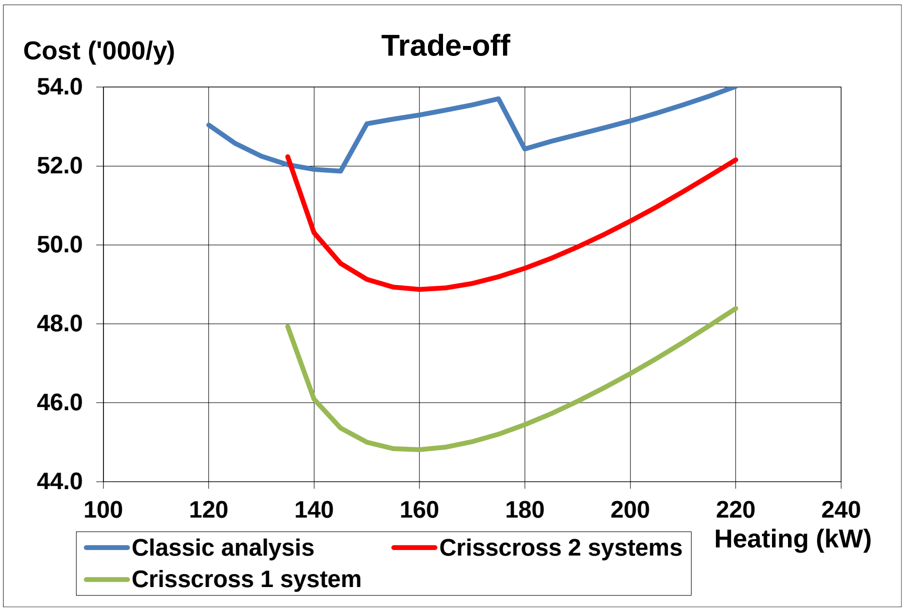


Figure 2.1

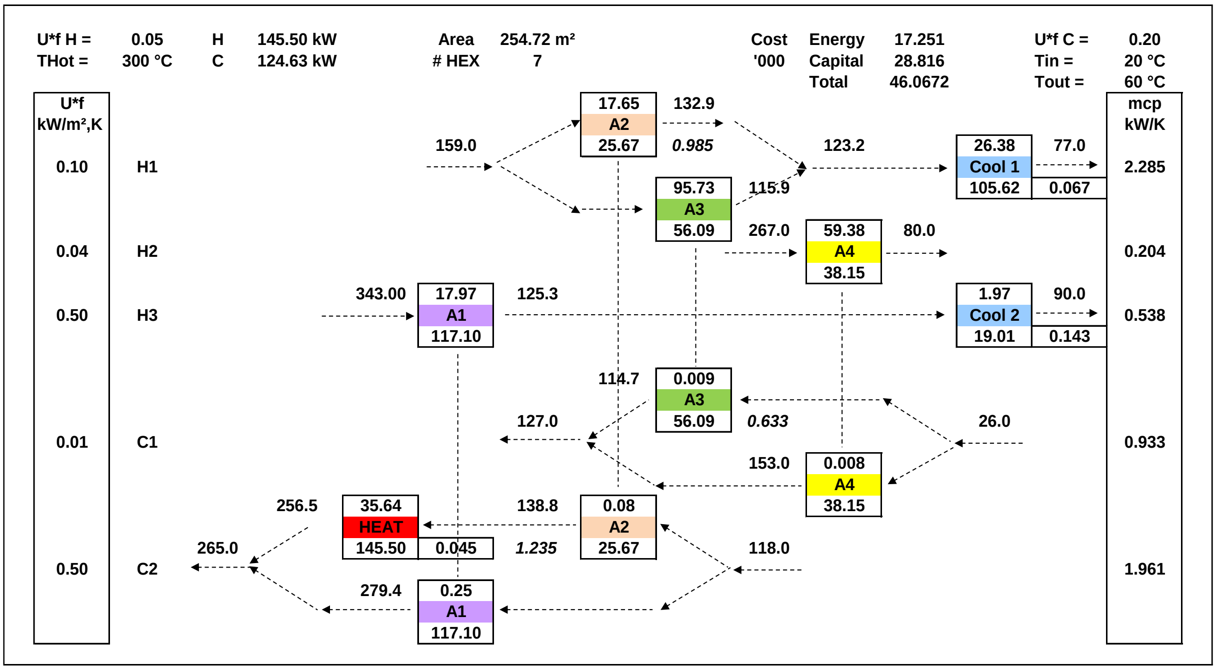


Figure 2.2

2.1.2 A second cost data set

The small-scale problem was also analysed with a different exchanger cost data set: HEX cost formula: 7400 + 80*Area $/year. This second data set was used by Adjiman et al. [17], Bergamini et al. [18], F. Pettersson [19], Bogataj et al. [20], Chang et al. [9], Caballero et al. [10] and Cerdá et al. [22].

The trade-off curves for the second data set are shown in Figure 2.3. The shape of the curves is the same as for the first cost data set, the level, however, is different.

Based on the grid, generated by the analysis, several initial networks can be developed using LP after reducing the number of integration bands to between 6 and 3.

The minimum number of units with 1 independent system is 6. Such network has a cost of 83.12 k$/year and is shown in Figure 2.4. With the relatively high fix cost in de exchanger cost function, there might be interest in further reducing the number of units. This is only possible by creating a second independent system, which can be done by removing exchanger A4 in Figure 2.4 and adjusting heating and cooling loads and the split ratio on cold stream C2. The resulting network has a cost of 79.99 k$/year and is shown in Figure 2.5. The are other possibilities to create two independent systems, with a higher cost, however.

The optimum network shown in Figure 2.5 can also be obtained by application of the simple heuristic rule “satisfy the smallest heat load first”. This would lead to the following steps:

- smallest: load on H2 (38.15 kW) satisfied with A1 on branch of C1
- next: 2nd branch of C1 (56.09 kW) satisfied with A2 on cold side H3
- next: hot side H3 (80.03 kW) satisfied with A3 on branch of C2
- next: load on H1 (187.37 kW) satisfied with Cooling
- next: 2nd branch of C2 (208.24 kW) satisfied with Heating.

Analysis of the data set prior to design reveals other possibilities. With the objective of achieving a minimum number of units (in view of the high exchanger fix unit cost), cooling of at least 138.13 kW (from Table 2.1) should be achieved with one single cooling unit. This is only possible with a cooler on hot stream H1 since the cooling demand cannot be satisfied with one single cooler on the other hot streams. Furthermore, such cooler on hot streams H2 and H3 would create a significant energy penalty to start with. With this assumption, an initial network automatically develops into the network in Figure 2.4. Further evolution, eliminating heat exchanger A4 leads to the optimum network in Figure 2.5. With a cooler load of 187.37 kW on H1, an initial network develops immediately into the optimum network of Figure 2.5. The network of Caballero et al. has the optimum structure and fine-tuning results in minimum cost.

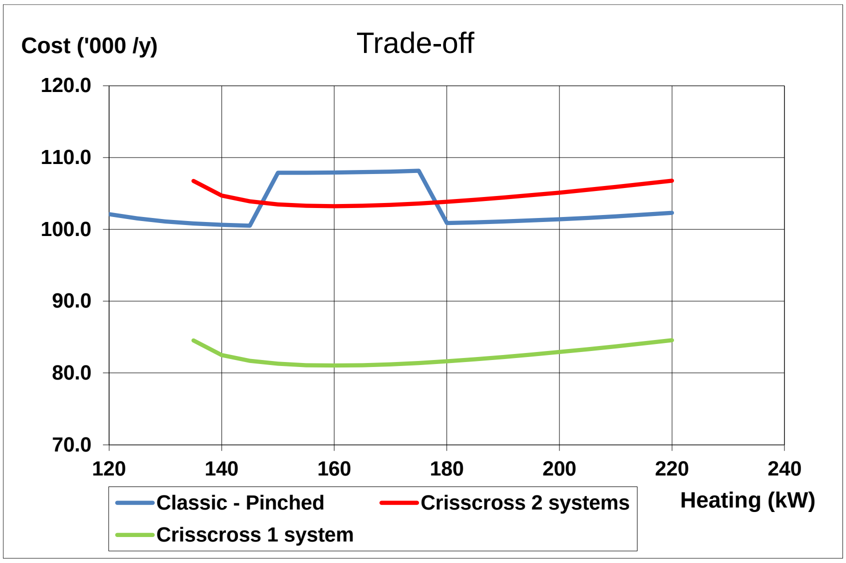
Results can be compared in Table 2.3.

Table 2.3

	Heating	Area	units	splits	Cost
	kW	m²	#	#	'000 $/y
Zamora	246.39	213.03	5	0	83.40
Adjiman 1°	246.39	200.72	5	0	82.42
Bergamini	246.39	213.03	5	0	83.40
Petterson (iso)	208.24	239.75	5	1	80.96
Bogataj (iso)	208.24	239.75	5	1	80.96
Chang (iso)	208.24	239.75	5	1	80.96
Caballero et al. 1°	208.2	227.80	5	2	80.00
Cerda et al. (non-iso)	208.24	238.35	5	1	80.85
This study					
non-iso	157.00	251.12	6	2	83.12
iso	208.24	232.49	5	2	80.36
non-iso	208.24	227.64	5	2	79.99

1° corresponds with the optimum solution after fine-tuning by the author

Figure 2.3



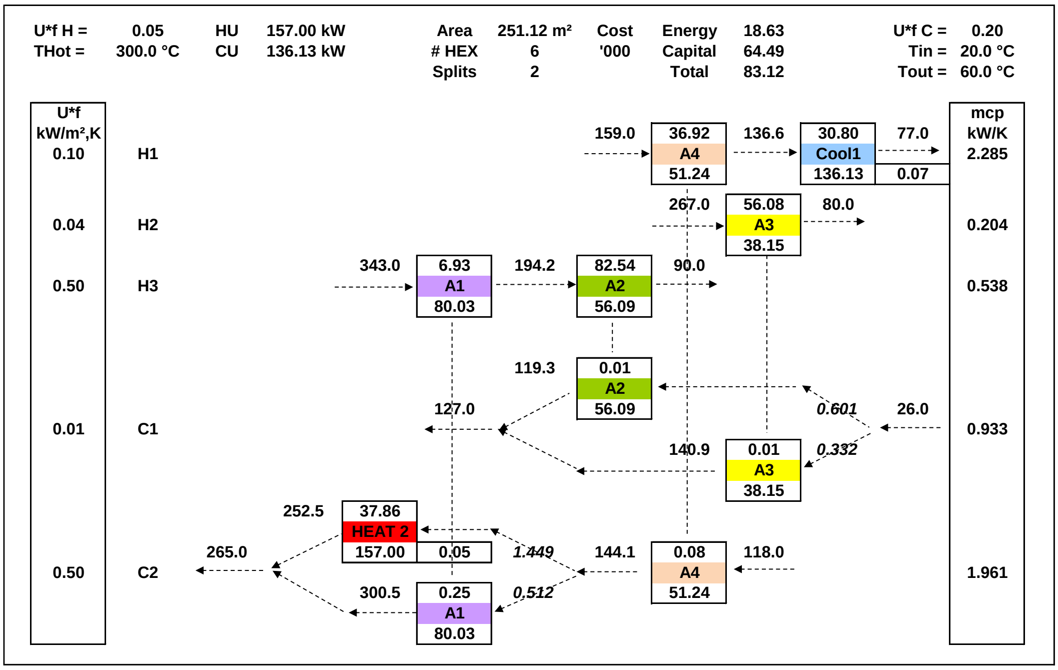


Figure 2.4

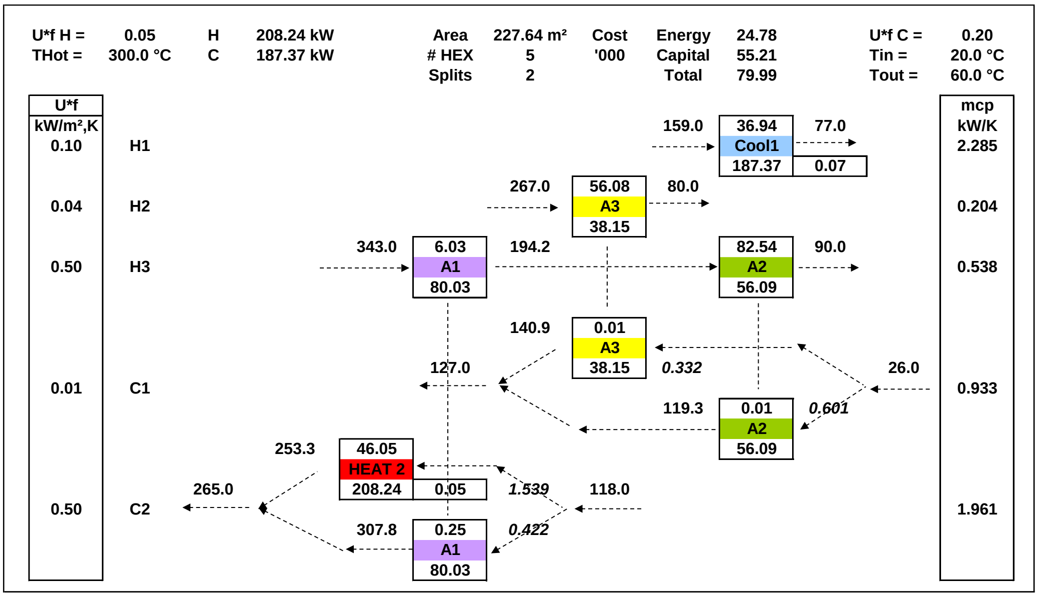


Figure 2.5

2.2 The mid-size problem

The mid-size case was studied by the author in [23]. The data of the process streams are shown in Table 2.4. The heat capacity flow rates are a factor of 10 larger than in the small-size case.

Table 2.4

Tsupply	Ttarget	Heat	DT-Shift	U*f	Descript
°C	°C	kW	K	kW/K,m²	-
159	77	1873.70	9	0.10	H1
267	80	381.48	21	0.04	H2
343	90	1361.14	0	0.50	H3
26	127	942.33	63	0.01	C1
118	265	2882.67	0	0.50	C2
300	300	1675.00	47	0.05	Heating
20	60	1466.32	0	0.20	Cooling

The shift values in Table 2.4 were obtained by crisscross optimisation prior to design. The heat load of 1675 kW has been chosen from the shape of the trade-off curves in Figure 2.6, based on the first cost data set as mentioned below.

2.2.1 A first cost data set

The problem was studied with a first cost dataset by S. Ahmad [24]. It was also studied by Rev & Fonio [25] and Serna and Jiménez [26], without cost calculations, however, and by Serna et al. [27], with different area cost values.

The following cost parameters were used by Ahmad:

- Hot utility 300°C - 299°C, Uhot 0.05 kW/m²,K, Cost 110 \$/kW,year
- Cold utility 20°C - 60°C, Ucold 0.20 kW/m²,K, Cost 10 \$/kW,year
- HEX cost formula: 874.0 + 438.15*Area$^{0.78}$ \$/year.

The grids from classic pinch analysis and from the crisscross procedure with respectively 11 and 10 vertical integration bands can be simplified and reduced to 6 bands without affecting the nature of the problem. The resulting grids are shown in Table 2.6.

From the grid diagram of the classic approach, it appears that a heater shall be allocated to cold stream C2 only. In the crisscross case, a heater will be put on cold stream C2 as well as on cold stream C1 because the heating utility and C1 lay in a common integration band. The optimum design worked out from the crisscross-grid with 9 units and a cost of 460.72 k$/year is shown in Figure 2.7. This network can be further developed into the network of Figure 2.8 with 8 units and a cost of 460.78 k$/year with a negligible cost penalty. Finally, deleting the heater on cold stream C1 will lead to the network in Figure 2.9 with 7 units and a cost of 463.60 k$, which means a cost penalty of only 0.63%. A couple of swaps, enabling the removal of the cooler on hot stream H3 lead to the network of Figure 2.10 with 6 units and a cost of 470.74 k$.

Analysis of the differences between the classic and the crisscross approach and of the impact of different starting values for the initial network leads to the following insight.
The optimum network shows a heater on cold stream C1 and a cooler on hot stream H3, each of which might be missing following the classic approach.
A heater will appear on cold stream C1 only if crisscross is applied to such an extent that the heating utility and the cold stream C1 come into a common integration band. Referring to Table 2.4 where shift values are optimized for minimum area, a heater will appear on cold stream C1 for heating loads of 1400 kW onwards. The trade-off suggested a heating load of 1675 kW and, indeed, this input generates a heater on cold steams C1 and C2 in the initial network.

A cooler will appear on hot stream H3 as soon as cooling down hot stream H3 with cold utility becomes attractive versus cooling it down with cold stream C1. This is achieved automatically in case of crisscross for heating loads of 1200 kW onwards. For lower heating loads, cold stream C1 does not move out of the cooling band automatically and no cooler will appear on hot stream H3. In the classic approach, a cooler will never appear on hot stream H3 automatically.

Results can be compared in Table 2.5

Table 2.5	Heating	Area	units	splits	Cost
	kW	m²	#	#	'000 $/y
Ahmad	1456.70	2600.12	9	3	503.71
This study	1621.14	2255.60	9	1	460.72
	1629.00	2281.16	8	1	460.78
	1457.70	2790.74	7	1	463.60
	1715.90	2341.45	6	2	470.74

Table 2.6

Process : **3H2C** **Version :** **Classic**

	area	**#HEX**	**AreaCost**
Heatit	2690.82	9	340.24
Design	2734.22	15	342.02

N°	Tsupply	Ttarget	Heat	Shift	Descriptior	U*f													
	°C	°C	kW	K	-	kW/m²,K	Bands	1		2		3		4		5		6	
6	300	299	1675.00		Heating	0.050			300.00		299.00								
1	159	77	1873.70		H1	0.100									159.00		138.43		77.00
2	267	80	381.48		H2	0.040					267.00		183.13		159.00		138.43		80.00
3	343	90	1361.14		H3	0.500	343.00		300.01		299.00		183.13		159.00		138.43		90.00
4	26	127	942.33		C1	0.010							127.00		126.72		60.00		26.00
5	118	265	2882.67		C2	0.500	265.00		253.21		167.51		127.00		118.00				
7	20	60	1466.32		Cooling	0.200											60.00		20.00

Process : **3H2C** **Version :** **Crisscross**

	area	**#HEX**	**AreaCost**
Heatit	2101.73	9	285.25
Design	2046.18	17	306.37

N°	Tsupply	Ttarget	Heat	Shift	Descriptior	U*f													
	°C	°C	kW	K	-	kW/m²,K	Bands	1		2		3		4		5		6	
6	300	299	1675.00	47	Heating	0.050			300.00		299.00								
1	159	77	1873.70	9	H1	0.100							159.00		137.68		128.74		77.00
2	267	80	381.48	21	H2	0.040					267.00		171.00		149.68		140.74		80.00
3	343	90	1361.14	0	H3	0.500	343.00		253.01		252.00		150.00		128.68		119.74		90.00
4	26	127	942.33	63	C1	0.010			127.00		103.03		77.30		55.00		26.00		
5	118	265	2882.67	0	C2	0.500	265.00		240.31		166.03		140.30		118.00				
7	20	60	1466.32	0	Cooling	0.200											60.00		20.00

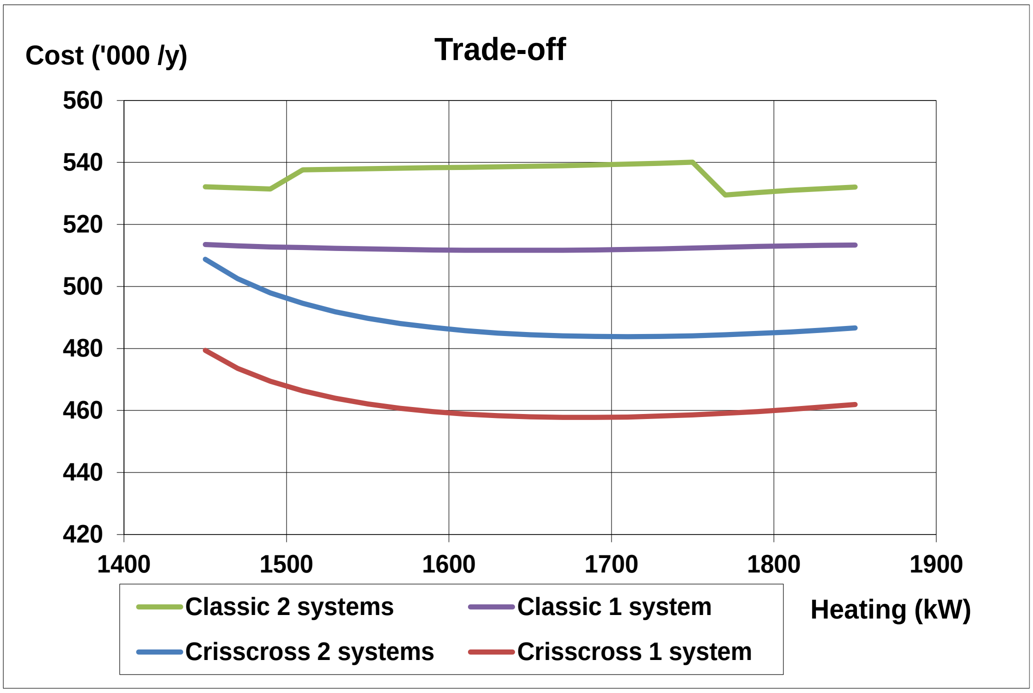


Figure 2.6

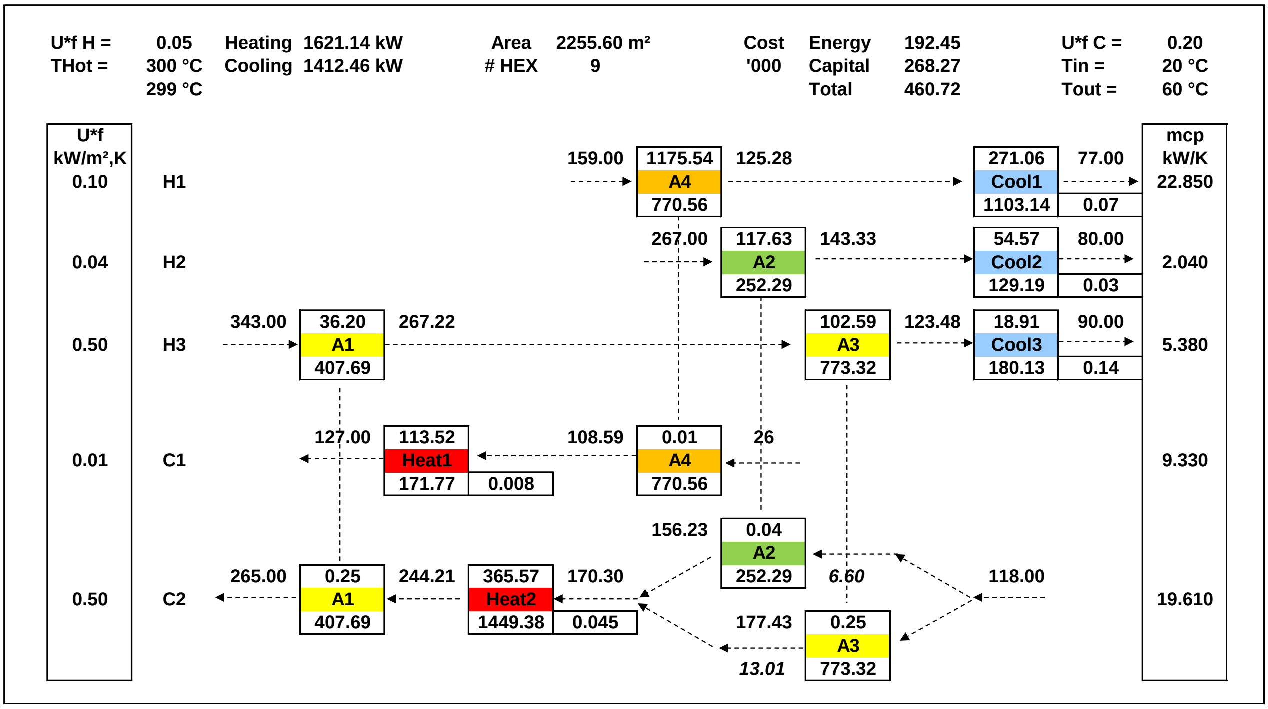


Figure 2.7

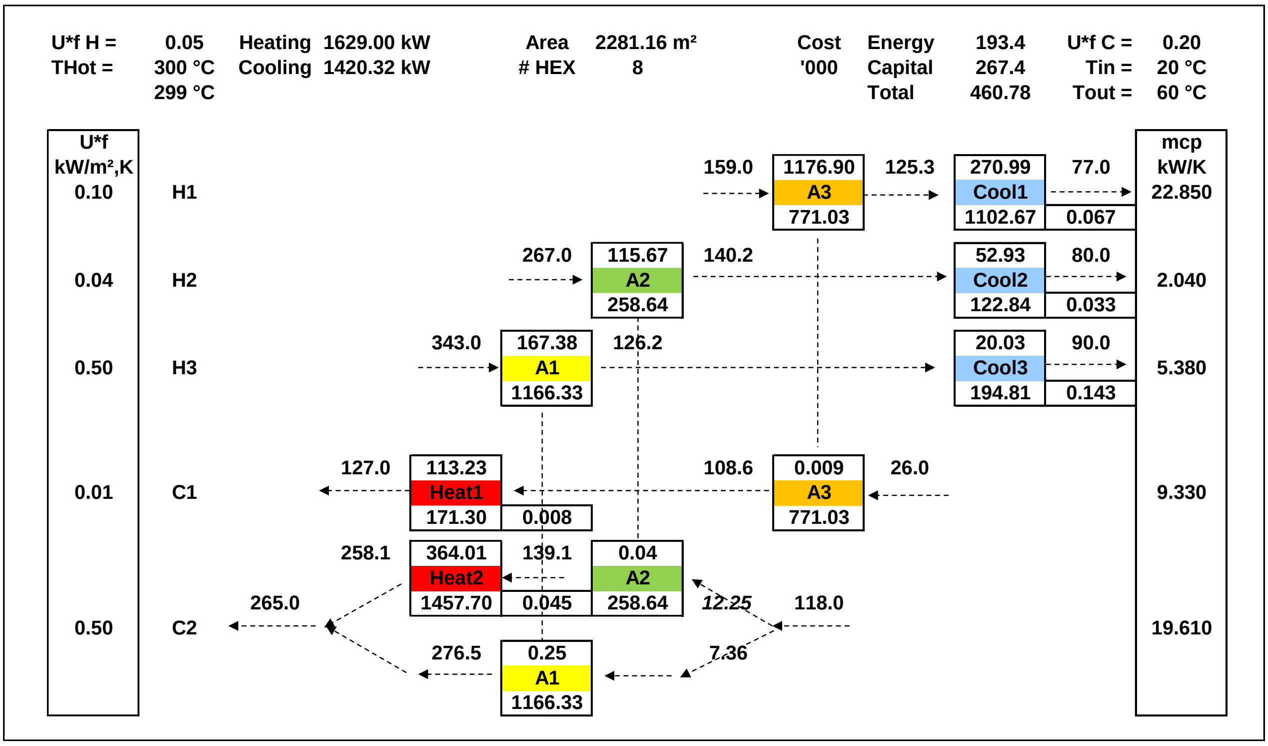


Figure 2.8

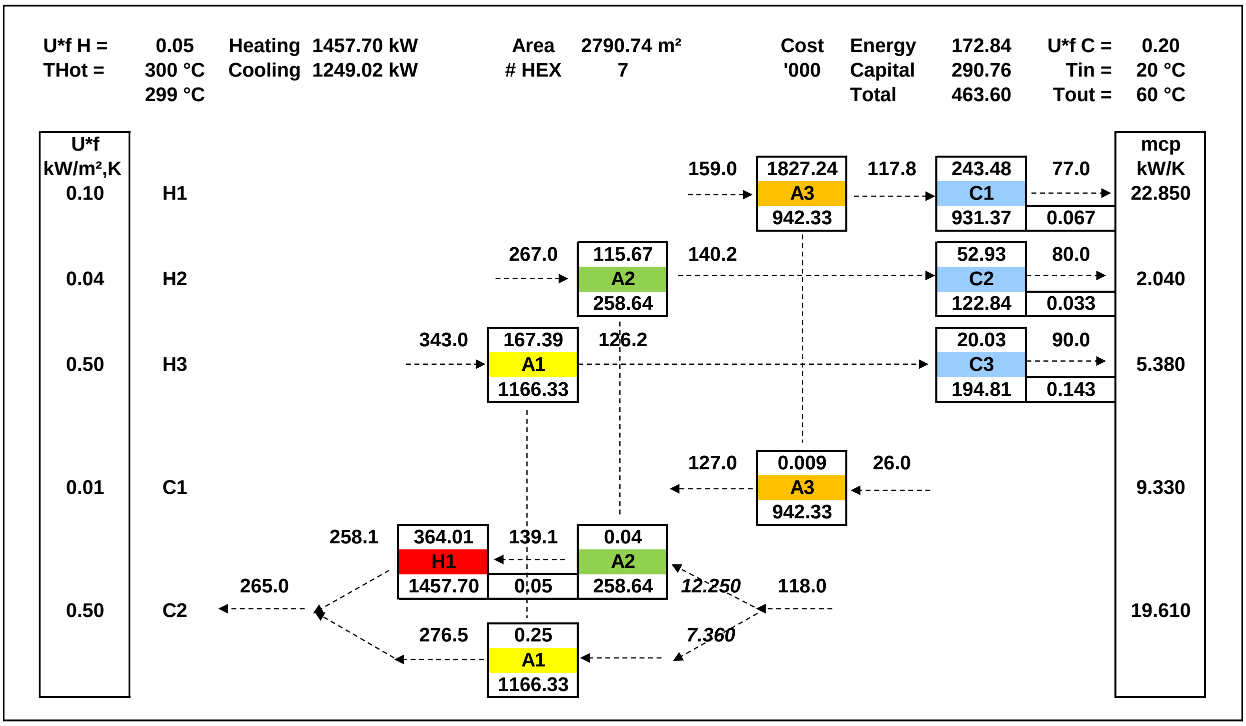


Figure 2.9

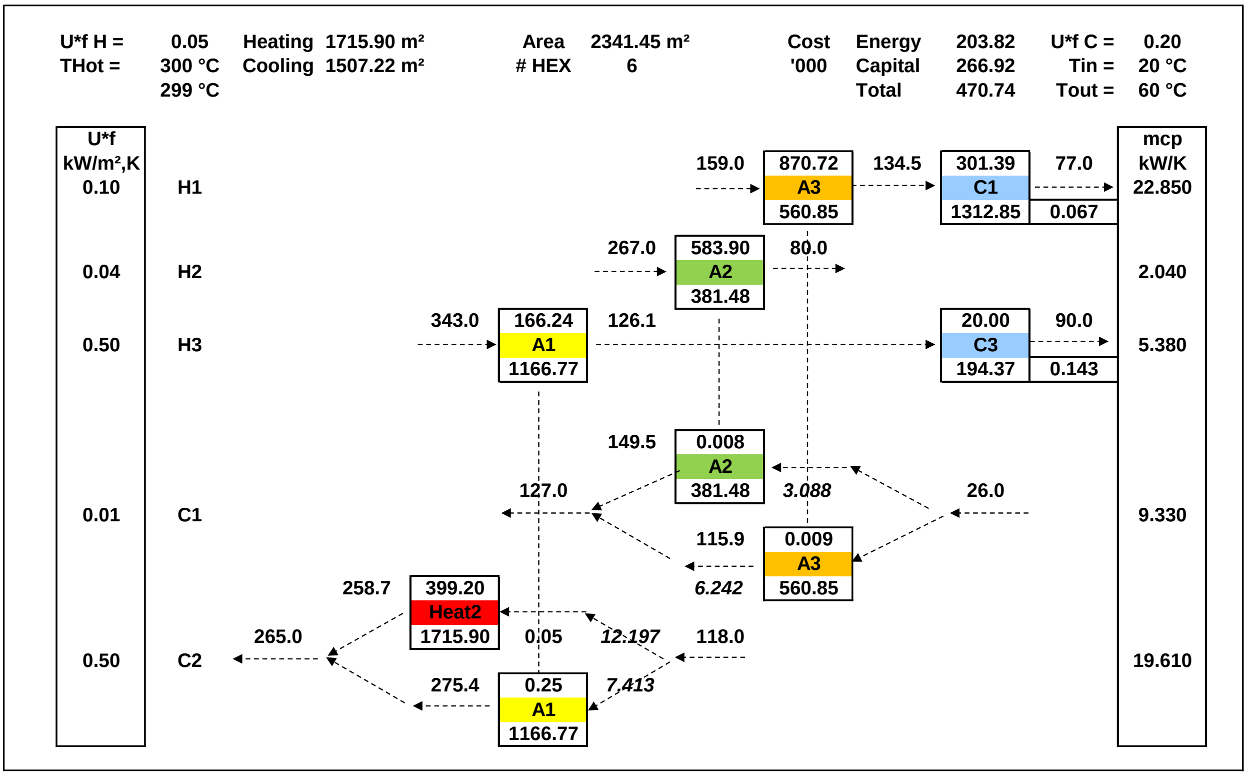


Figure 2.10

2.2.2 A second cost data set

This stream configuration was also used by Ning Jiang et al. [29], with the following cost data:

- Hot utility 300°C - 299°C, Uhot 0.05 kW/m²,K, Cost 80 $/kW,year
- Cold utility 20°C - 60°C, Ucold 0.20 kW/m²,K, Cost 20 $/kW,year
- HEX cost formula: 1300*Area$^{0.60}$ $/year.

The trade-off curve is shown in Figure 2.11.

The design approach by Jiang et al. was based on the diverse pinch concept, developed by Ahmad, a methodology also followed by Rev and Fonio and by Serna et all. The approach in the present study was based on pinch analysis with crisscross optimisation prior to design.

The network developed here has 7 units for a cost of 411.64 k$/year and is shown in Figure 2.12. Results can be compared in Table 2.7.

Table 2.7	Heating	Area	units	splits	Cost
	kW	m²	#	#	'000 $/y
Jiang	2067.88	1842.31	11	3	478.20
This study	1465.00	2784.91	7	1	411.64

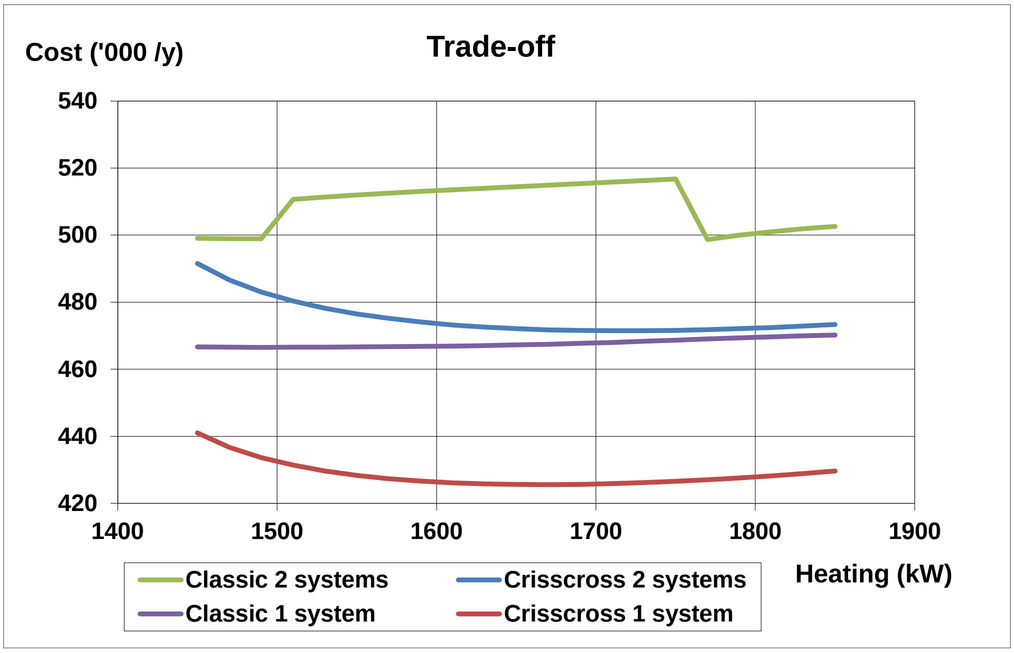


Figure 2.11

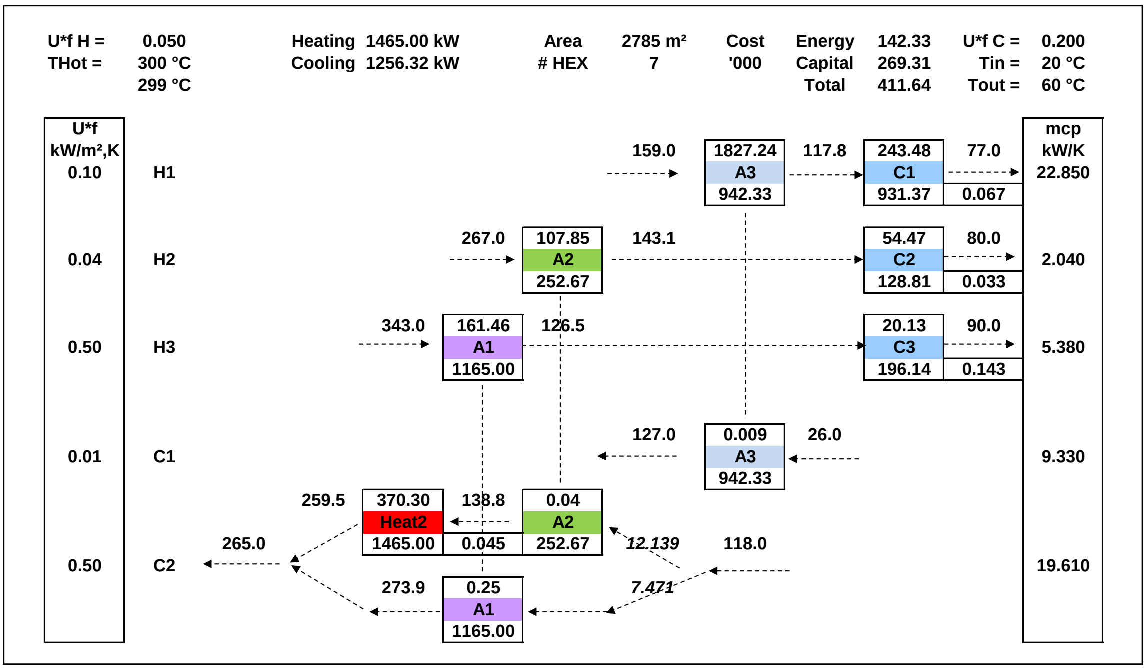


Figure 2.1

2.3 The large-size problem

2.3.1 Data set from Gundersen et al.

The data set of the large-size problem treated here was taken from T. Gundersen et al. [29]. It was also used by Miguel Velazquez [30].

The data set is given in Table 2.8 with shift values optimised with the crisscross procedure for minimum surface area. The heat transfer coefficients are not different from each other with an order of magnitude as in the small and medium-sized problem, so, the shift values are much smaller. The challenge of dealing with unequal heat transfer coefficients is no longer present.

Table 2.8

Tsupply	Ttarget	Heat	DT-Shift	U*f	Descript
°C	°C	kW	K	kW/K,m²	-
159	77	18737	-1.0	0.40	H1
267	88	3652	0.0	0.30	H2
343	90	13611	1.0	0.25	H3
26	127	9423	6.0	0.15	C1
118	265	28827	0.0	0.50	C2
376	376	10050	0.0	1.00	Heating
15	30	7800	0.0	0.60	Cooling

Cost data

Heating : 110 /kW,year Cooling : 10/kW,year

HEX Cost : 8600 + 670 x Area$^{0.83}$ $ Annuity factor : 0.3221

The heating load has been chosen on the basis of the trade-off curves, illustrated in Figure 2.13, as the average between the two minimums and would correspond with an overall DTMin of 7°C in classic pinch analysis.

The authors in the paper by Andres Barbaro et al. [31] refer to the same problem as above; the stream data set has the same structure, but heat loads and heat transfer coefficients are smaller with a factor 3.6, which would lead to similar exchanger areas. HEX costs are the same, but energy prices are not mentioned; to restore congruency, energy prices should be increased by a factor of 3.6. Hence, it was assumed that the latter authors' objective was to study the same problem as presented by Gundersen and Grossmann.

The hot utility temperature of 376°C is higher than the hottest hot stream, which simplifies the design task significantly. It should be noted, however, that a hot utility with a condensing temperature of 376 °C is unusual, the critical point of steam being at 375°C. It is unclear which kind of utility was considered.

Results and comparison of solutions are shown in Table 2.9.
The networks of this study are shown in Figure 2.14 and Figure 2.15 for respectively 9 and 8 heat exchanger units. The difference in the structure of the solutions is limited.

Table 2.9	Heating	Area	units	splits	Cost
	kW	m²	#	#	'000 $/y
Gundersen et al. °)	10465.2	7178.63	8	3	1748.00
Barbaro et al.	10465.2	6994.35	8	3	1739.12
Velazquez	12411.0	5455.16	8	1	1862.86
This study	10067.0	7948.23	9	2	1722.05
	10090.0	7988.61	8	3	1722.08

°) isothermal splits

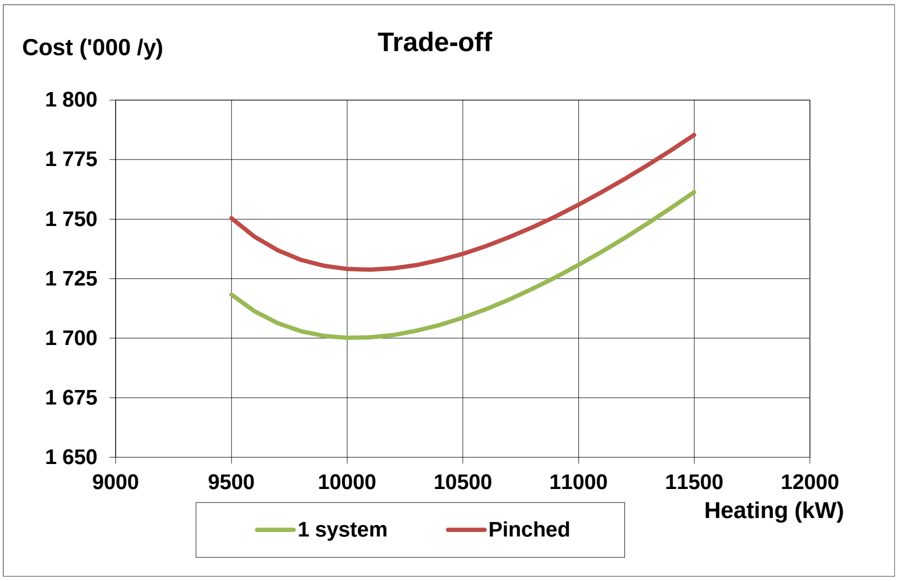


Figure 2.13

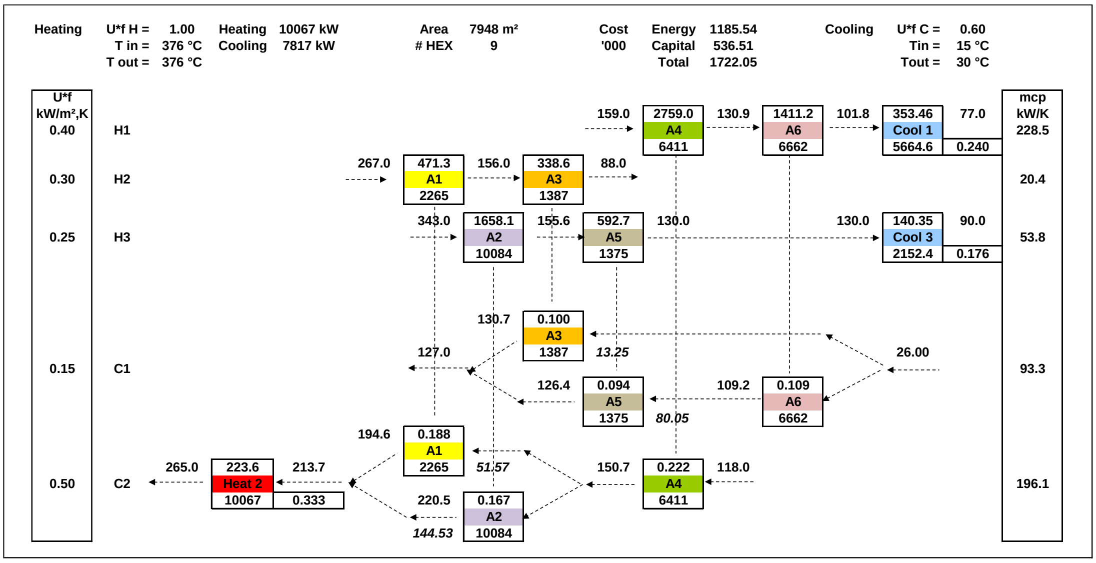


Figure 2.14

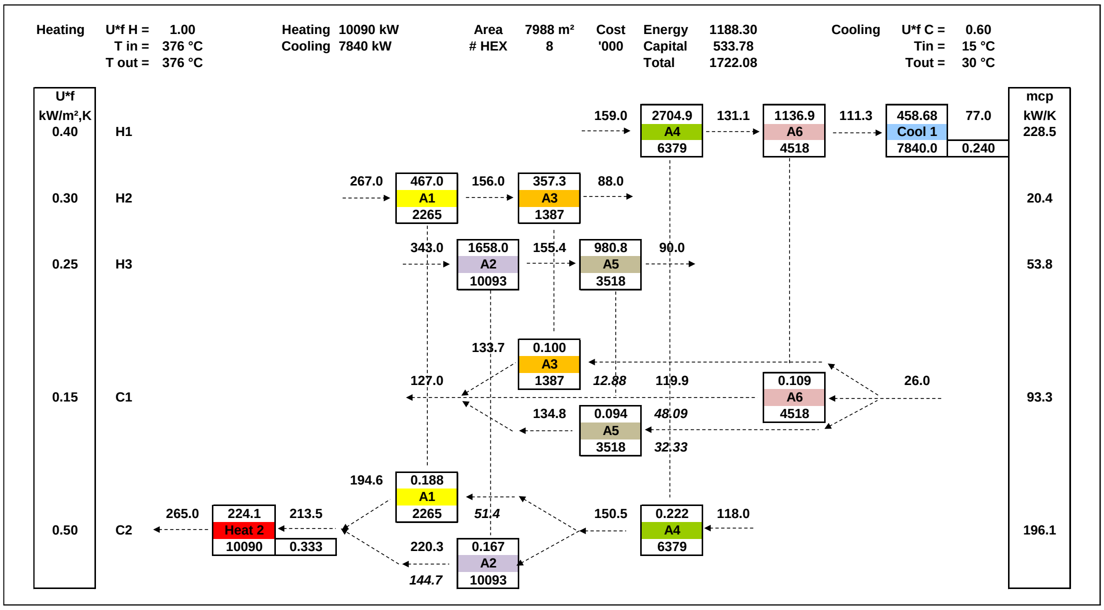


Figure 2.15

2.3.2 Dataset from Kim et al.

Later authors have used different utility and investment cost data as follows:

- Hot utility 500°C - 499°C, Uhot 0.53 kW/m²,K, Cost 100 $/kW,year
- Cold utility 20°C - 40°C, Ucold 0.53 kW/m²,K, Cost 10 $/kW,year
- HEX cost formula: 25000 + 55 * Area $/year.

Among those authors are: Sung Young Kim et al .[32], Pavão et al. [33], Chang et al. [9] and Caballero et al. [10]. As was already the case in the previous utilities' data set, a condensing temperature of 500°C is unusual. It simplifies the generation of a network but becomes an academic exercise, unfortunately without any practical industrial significance.

The trade-off curve is shown in Figure 2.16. The results are shown in Table 2.10.

Table 2.10

		Heating	Area	units	splits	Cost
		kW	m²	#	#	'000 $/y
Kim	1°	11700.0	5703.21	8	2	1778.18
Pavao et al.	2°	10316.7	7482.10	8	3	1723.85
Chang et al.	2°	11299.2	6145.87	8	3	1758.38
Caballero et al.	3°	10453.3	7321.71	8	2	1730.06
This study	2°	10316.6	7482.26	8	3	1723.85
	3°	10374.0	7463.79	8	2	1729.15
		10339.0	7512.14	9	1	1752.96

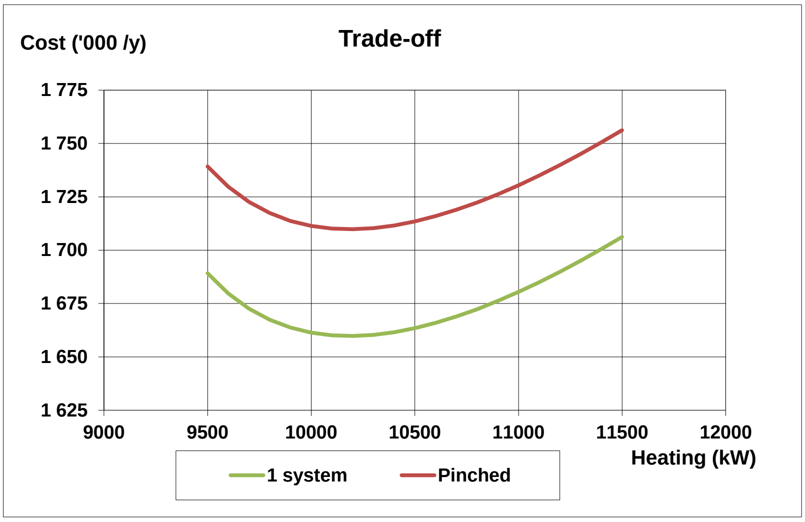
1° revised by author

2° Networks with similar structure

3° Networks with similar structure

The network with the lowest cost of 1723.85 k$/year is shown in Figure 2.17. It has an area of 7482.26 m², 8 units and 3 splits. A network with the same structure was developed by Pavao et all. and by Chang et all., the latter, however, with iso-thermal splits. A network with only 2 splits and a cost of 1729.15 k$/year is shown in Figure 2.18. It should be noted that the cost of splits has not been accounted for. The additional cost is only 0.31% and having a cooler on hot stream H2 might be an operational advantage. A network with only 1 split is shown in Figure 2.19. It has 9 units, also a cooler on hot stream H3 and has a cost of 1752.96 k$/year. The difference in energy consumption between the 3 alternatives is negligible. Many alternative networks can be developed with a cost within a range of 2% above the theoretical best alternative.

Figure 2.16



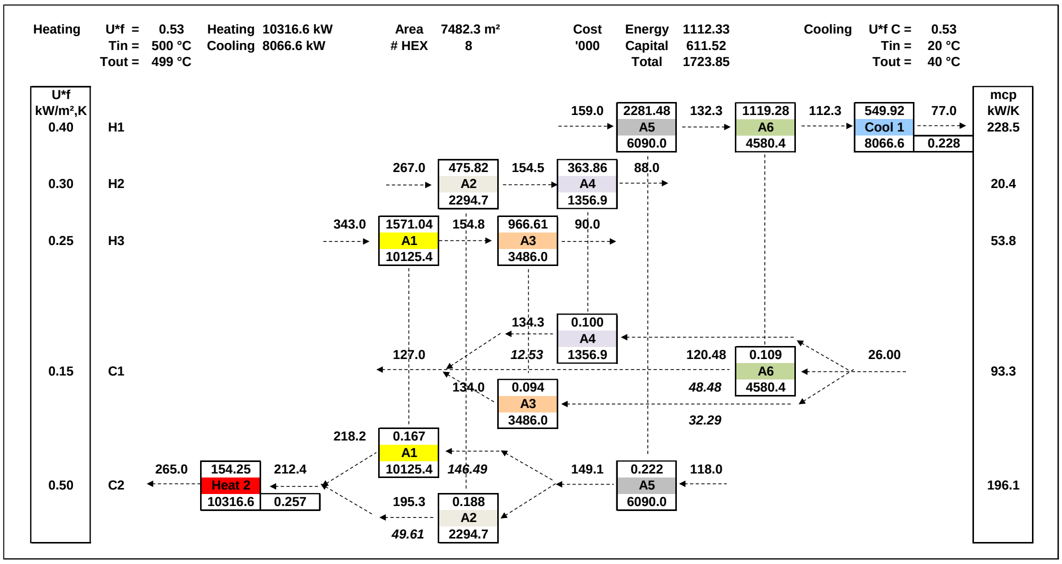


Figure 2.17

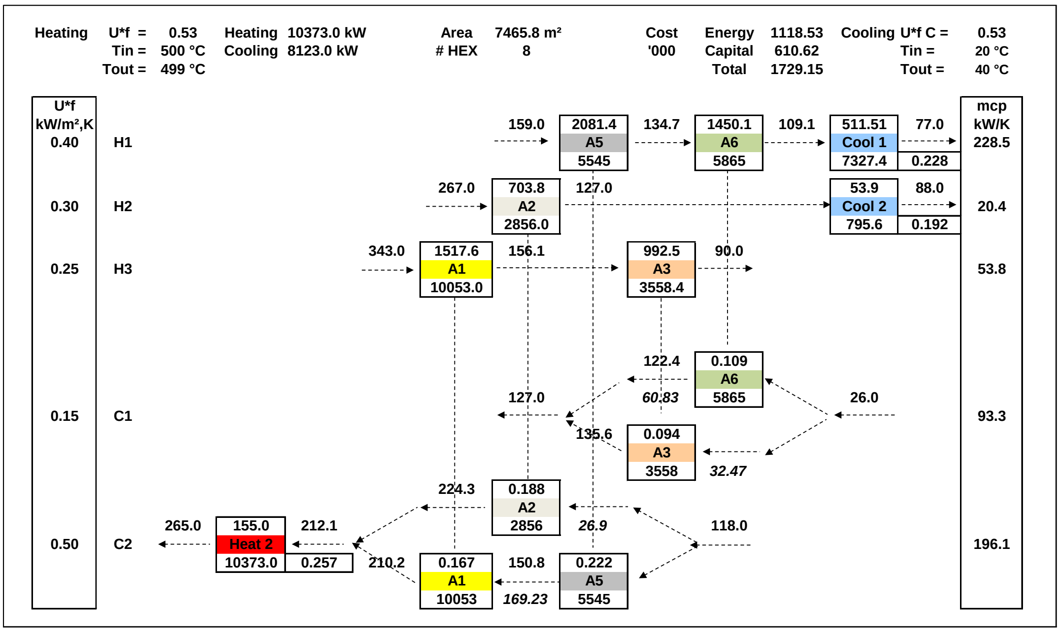


Figure 2.18

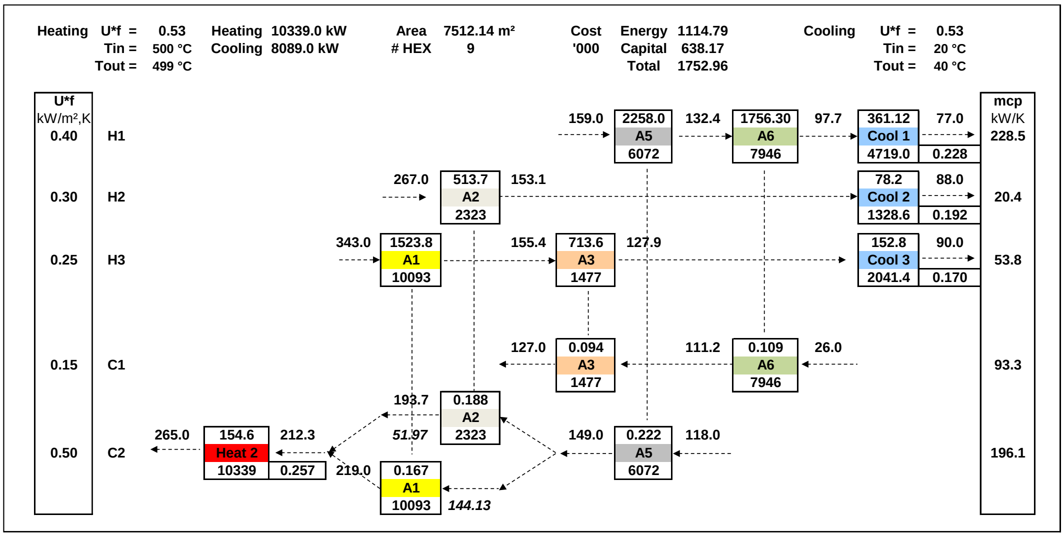


Figure 2.19

3 Example from Björk and Westerlund.

The data set of this theoretical case was set up by Björk et al. to illustrate a global optimisation strategy [35]. It was also studied by Laukkanen et al [36], by Huang et al. [37], by Pavao et al. [38], by Aguitoni et al. [39] and by Cerdá et al. [40].

The data set is shown in Table 3.1.

Table 3.1

	Tsupply	Ttarget	Heat	DT-Shift	U*f	Descript
	°C	°C	kW	K	kW/K,m²	-
	155	30	1000	5.0	2.00	H1
	80	40	600	5.0	2.00	H2
	200	40	2400	5.0	2.00	H3
	20	160	2800	5.0	2.00	C1
	20	100	1200	5.0	2.00	C2
	220	220			2.00	Heating
	20	30			2.00	Cooling

Heating : 120 \$ /kW,year   Cooling : 20 \$/kW,year

HEX Cost : 6000 + 600 x Area$^{0.83}$ \$/year

The available heat in the hot streams equals the available heat in the cold streams and for the given overall DTMin of 10K the problem becomes a double threshold problem. The high investment versus energy cost also drives the system into a threshold problem without heating.

Composite curves are shown in Figure 3.1. The pinch is caused by the 2 cold streams; a near-pinch is caused by hot stream H2. Networks can be developed using pinch design rules starting at the pinch at 20°C. Splitting cold stream C1 is required. The resulting network with 5 units can be developed into a network with 4 units with a cost of 95.66 k\$/year as shown in Figure 3.2.

The grid generated by pinch analysis has 5 integration bands. The number of bands can be reduced to 4, respectively to 3 by merging adjacent bands as shown in Table 3.2. Application of LP to the 5-bands grid generates an initial network with 12 units; respectively 10 units with the 4-bands grid and 8 units with the 3-bands grid. All initial networks can be developed by incremental evolution and distortion of the solution space to the network shown in Figure 3.2. The networks with 10 and with 8 units offer another opportunity, shown on the 8-bands network in Figure 3.3. The indicated node on cold stream C1 can be worked out into a smart node [41] in Figure 3.4. Incremental evolution of this network leads to the network with minimum cost in Figure 3.5. This network has 2 splits. Elimination of the branch with an mcp of 1.33 kW/K leads to the network in Figure 3.6 with a cost that is only 70 \$/year more expensive whilst a split has been saved.
The results can be compared in Table 3.3.

Table 3.2

Streams	mcp	Bands										
	kW/K		1		2		3		4		5	
H1	8.00			155.00		132.17		80.00		40.00		30.00
H2	15.00							80.00		40.00		
H3	15.00	200.00		155.00		132.17		80.00		40.00		
C1	20.00	160.00		126.25		100.00		65.71		22.29		20.00
C2	15.00					100.00		65.71		22.29		20.00

Streams	mcp	Bands								
	kW/K		1		2		3		4	
H1	8.00			155.00		80.00		40.00		30.00
H2	15.00					80.00		40.00		
H3	15.00	200.00		155.00		80.00		40.00		
C1	20.00	160.00		126.25		65.71		22.29		20.00
C2	15.00			100.00		65.71		22.29		20.00

Streams	mcp	Bands						
	kW/K		1		2		3	
H1	8.00			155.00		80.00		30.00
H2	15.00					80.00		40.00
H3	15.00	200.00		155.00		80.00		40.00
C1	20.00	160.00		126.25		65.71		20.00
C2	15.00			100.00		65.71		20.00

Table 3.3	Heating	Area	units	splits	Cost
	kW	m²	#	#	'000 $/y
Björk et al. °1)	-	217.88	4	1	95.66
Laukkanen	12.0	207.58	7	1	114.25
Huang et al. °2)	-	215.04	4	2	94.75
Pavao et al. °1)	-	217.88	4	1	95.66
Aguitoni et al. °1)	-	217.88	4	1	95.66
Cerdá et al. 3°)	-	211.45	5	1	101.16
This study					
°1)	-	217.88	4	1	95.66
°2)	-	215.04	4	2	94.75
	-	215.41	4	1	94.82

°1) same solution

°2) same solution

°3) adjusted for non-iso split

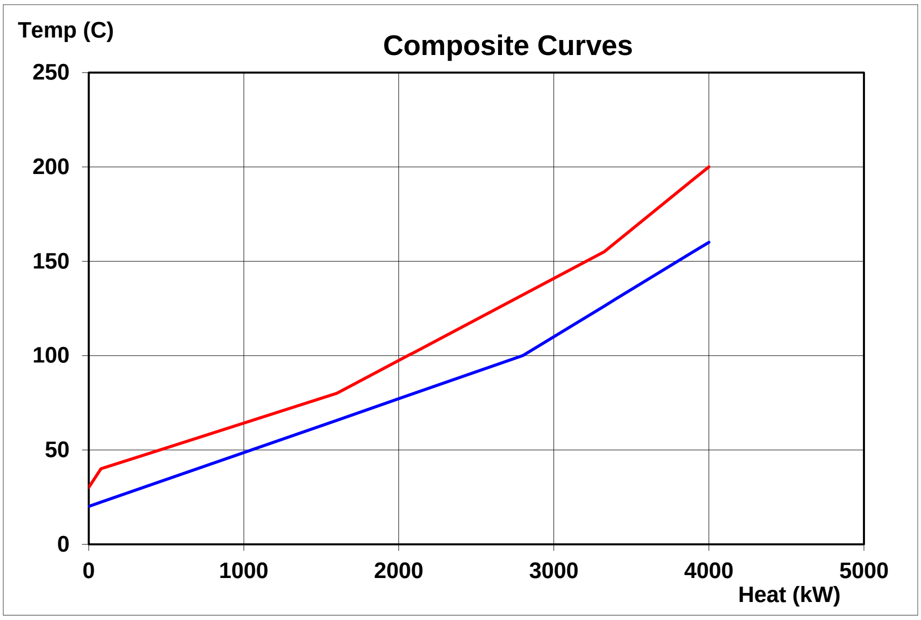


Figure 3.1

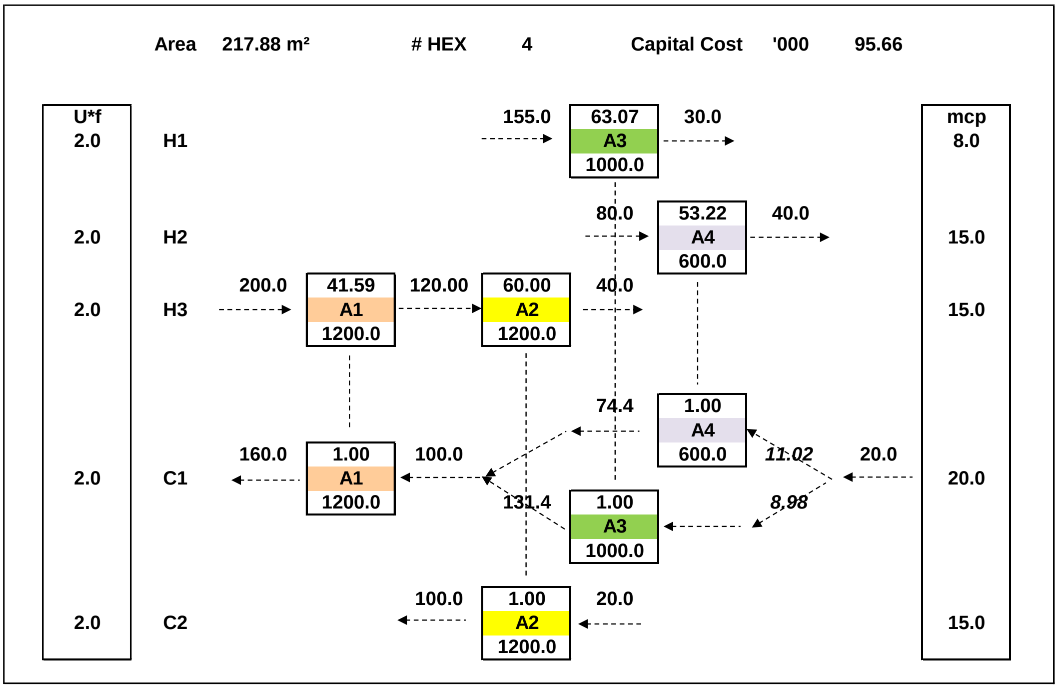


Figure 3.2

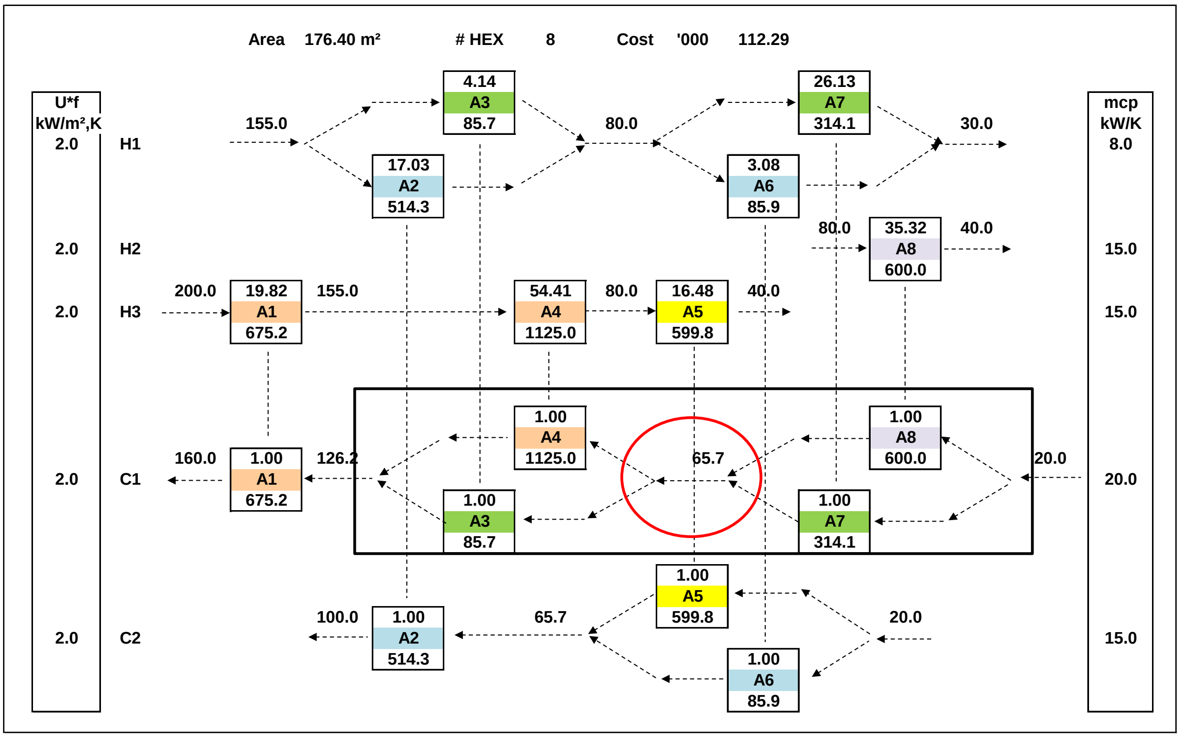


Figure 3.3

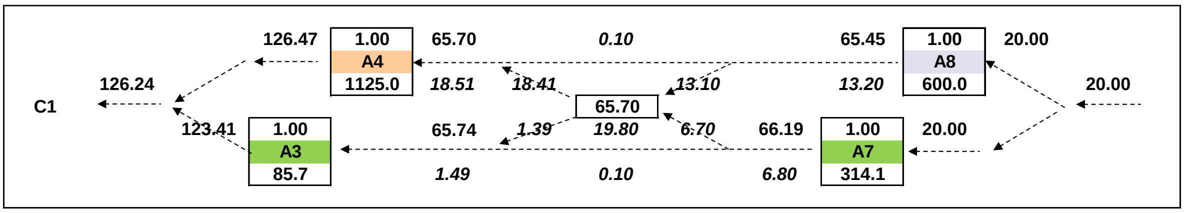


Figure 3.4

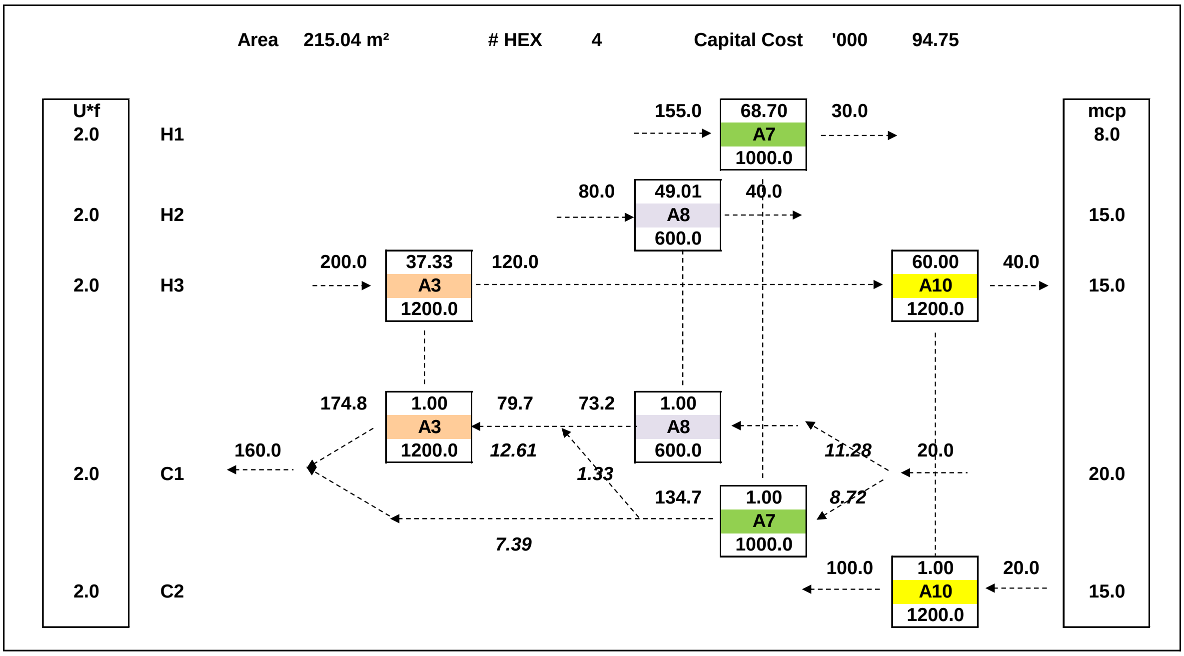


Figure 3.5

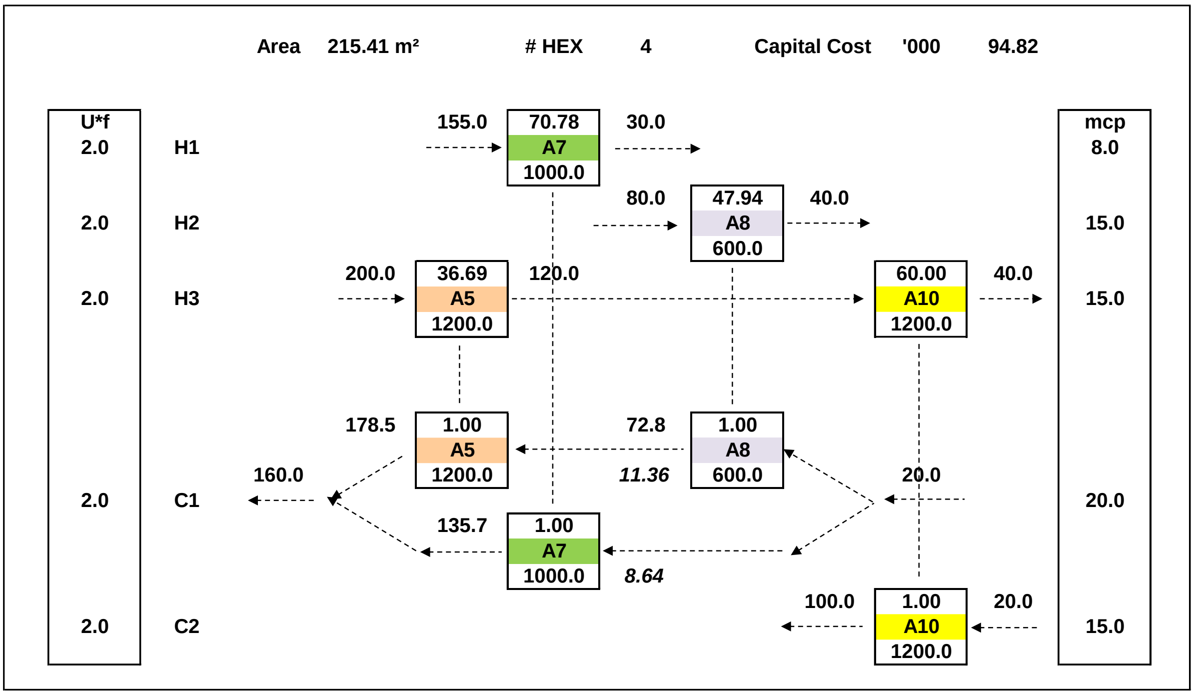


Figure 3.6

4 Example from Barbaro et al.

This problem, originally from Bagajewicz, Rodera and Savelski (2002) was studied by Barbaro et al [42]; it consists of 3 hot and 4 cold process streams and 1 heating utility. The data set is given in Table 4.1.

Table 4.1

Tsupply °C	Ttarget °C	Heat MJ/h	Shift K	U*f MJ/h,K,m²	Description -
100	30	13020	5.0	0.4	H1
75	30	7560	5.0	0.4	H2
50	30	480	5.0	0.4	H3
20	100	16800	5.0	0.4	C1
20	75	4620	5.0	0.4	C2
20	40	1680	5.0	0.4	C3
40	67	1740	5.0	0.4	C4
180	179	3780		0.4	Heating
10	20	0		1.0	Cooling

Cost data
Heating : 36.11 $/MJ/h,year   Cooling : 5.56 MJ/h,year
HEX cost = $3221 + 257.68 \text{ x } A^{0.8}$ $/year

The problem was presented as a threshold problem for a DTMin of 10K and was treated as such by the authors in [4.1]. Composite curves are shown in Figure 4.1. The curves are almost parallel, which is confirmed in the driving force diagram in Figure 4.2. The pinch is caused by cold stream C1.

The trade-off curve, shown in Figure 4.3 would suggest a non-threshold problem with a heating load of around 6750 MJ/h. The problem was solved as a threshold problem first without EMAT constraint; the resulting network, shown in Figure 4.4 has 7 units and 1 split for a cost of 712.60 k$/year. The problem was then solved as a non-threshold problem leading to the networks in Figure 4.5. This network has a cost of 656.46 k$/year, 9 units and 2 splits. From there, networks with 9 units and less splits can be developed, as well as networks with 8 and 7 units as shown in Figure 4.6 respectively Figure 4.7.

The results can be compared in Table 4.2.

Table 4.2		Heating	Area	units	splits	Cost
	EMAT	MJ/h	m^2	#	#	'000 $/y
Barbaro et al.	10K	3780.0	10018.8	9	5	766.56
This study -Threshold						
Target	10K	3780.0	9946.1	7	-	759.14
Network	5.7	3780.0	10401.5	7	1	712.60
This study - Non-threshold						
Target	-	6750.0	5804.2	8	-	686.61
Networks	-	5504.0	7074.03	9	2	656.46
	7.8	5292.0	7390.3	8	1	658.42
	7.8	8400.0	5257.3	7	1	692.38

Figure 4.1

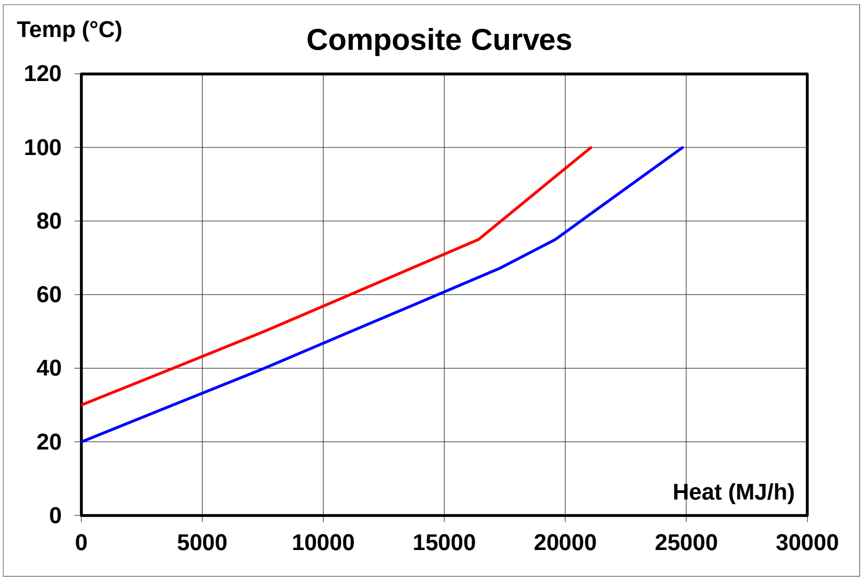
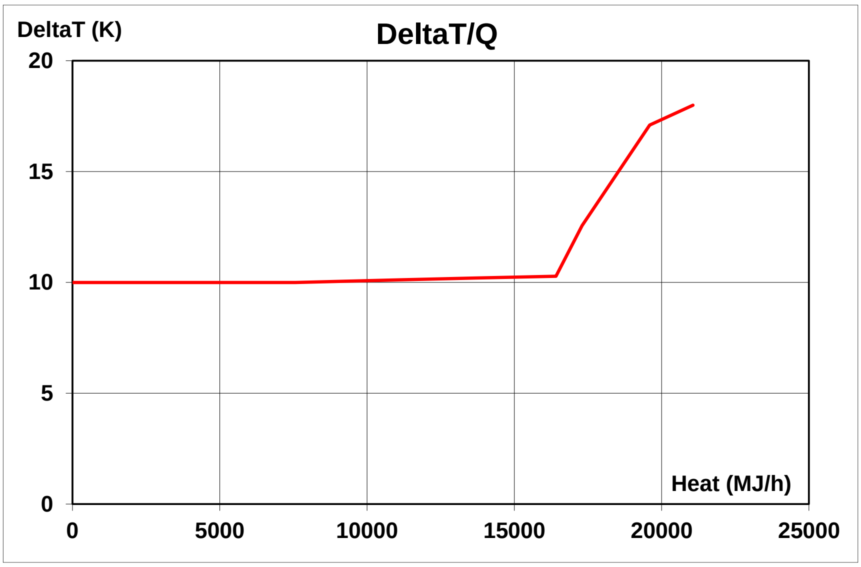


Figure 4.2



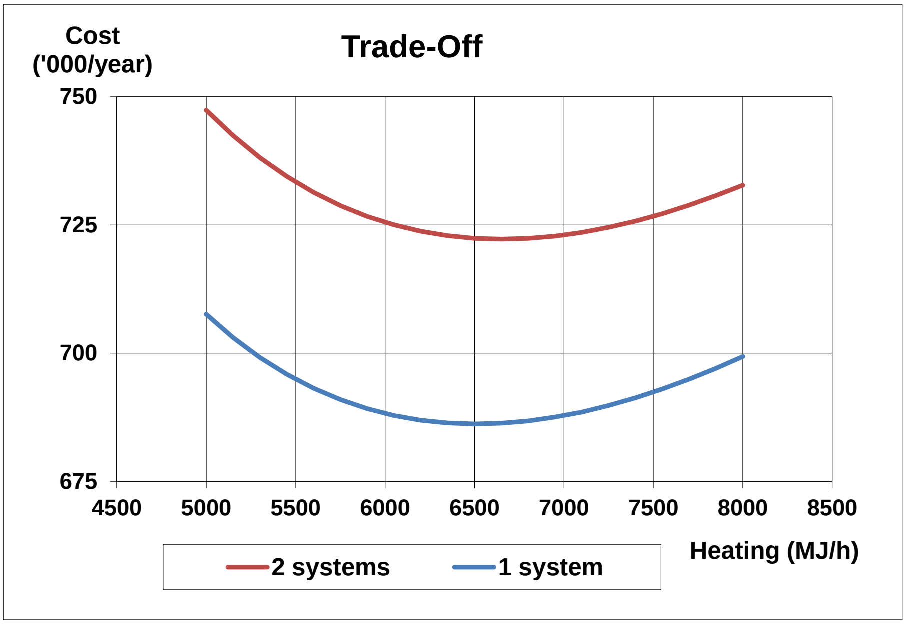


Figure 4.3

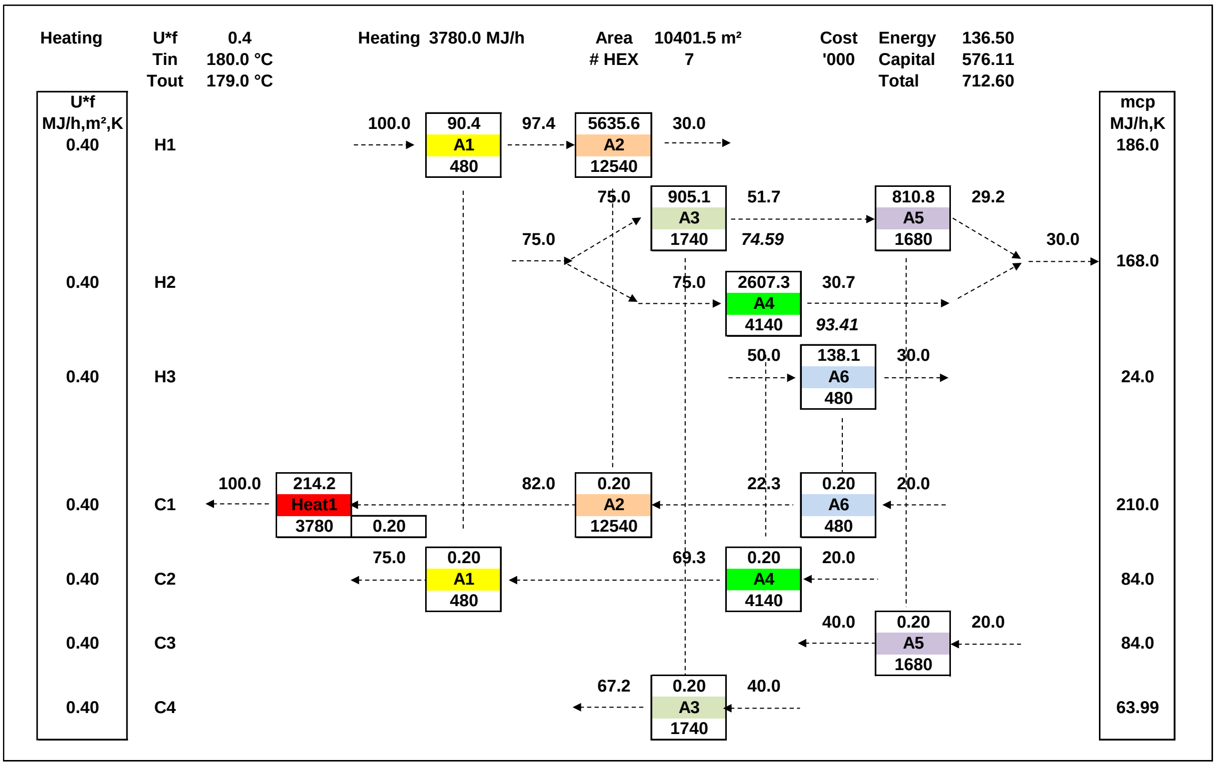


Figure 4.4

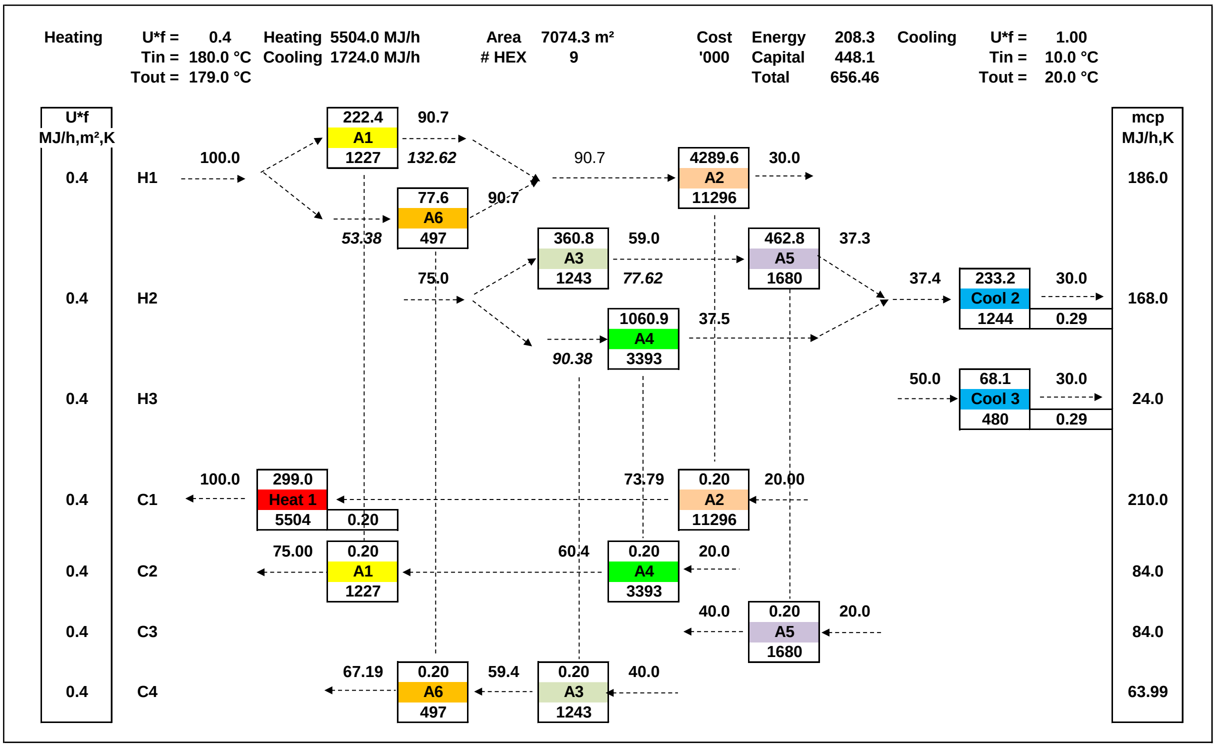


Figure 4.5

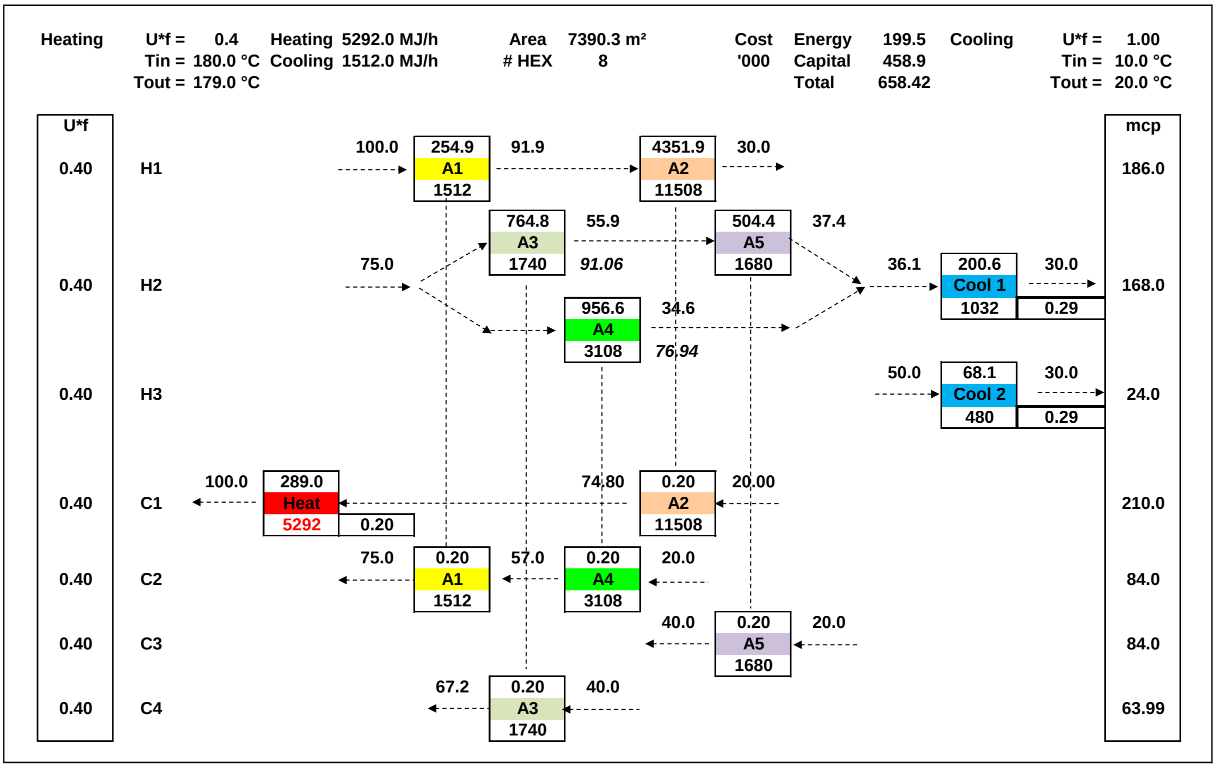


Figure 4.6

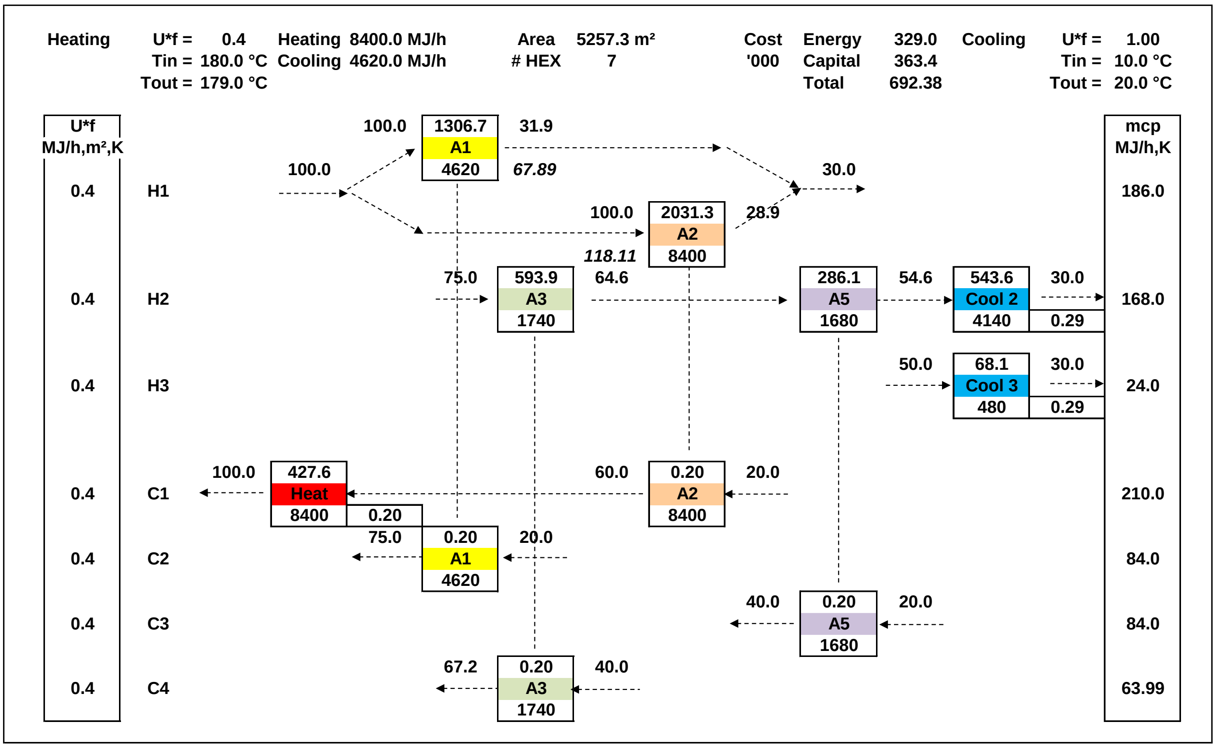


Figure 4.7

5 Examples from Ziyatdinov et al.

The following 4 examples were taken from Ziyatdinov et al. [43].

Composite curves for all examples are shown in the paper [44] and will not be reproduced here unless required. In the paper, a new stream-splitting procedure SSHEN (Split Stream Heat Exchange Net) was applied and compared with the results obtained by using SYNHEAT (a MINLP program for optimizing a staged HEN superstructure) with two optimization algorithms when addressing the problem of heat exchange systems synthesis: the DICOPT code and the global optimization code BARON. The BARON code produced the best results, which will be withheld for comparison.

5.1 The 4-steam problem.

The data set for the first problem is shown in Table 5.1. This problem was also studied by Cerda et al. [40].

Table 5.1

Tsupply K	Ttarget K	Heat kW	DT-Shift K	U*f kW/K,m²	Descript -
430	380	2000	2.5	1.800	H1
425	424.9	3000	2.5	1.900	H2
410	410.1	4000	2.5	1.700	C1
390	420	900	2.5	1.850	C2
627	626.9	700		2.500	Heating
303	315	800		1.000	Cooling

Cost data

Heating : 100.0 $/kW,year   Cooling : 10.0 $/kW,year

HEX cost :   380 x Area$^{0.65}$ $/year

The data set was analysed for a global DTMin of 5 K, resulting in heating and cooling loads as shown in Table 5.1. The trade-off curve (Figure 5.1) would suggest a heating load of around 575 kW. For reasons of comparability, however, the global DTMin of 5 K was maintained.

The network produced by SYNHEAT (Baron) is shown in Figure 5.2. It has a cost of 106.81 k$/year. The network following pinch design rules is shown in Figure 5.3; it has the same cost; the split can be avoided, and the network synthesis procedure is much simpler than with SYNHEAT. The network developed by Cerda et al. has a cost of 108.71 k$/year.

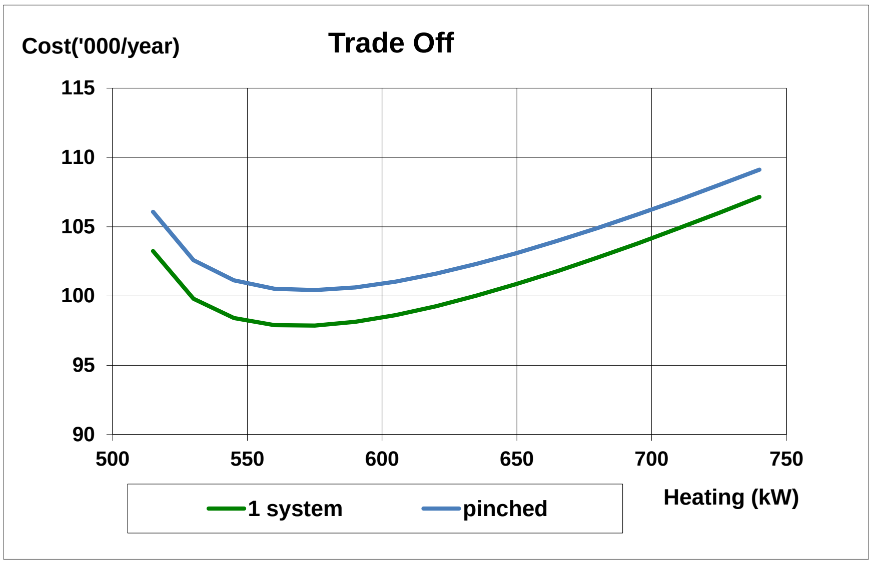


Figure 5.1

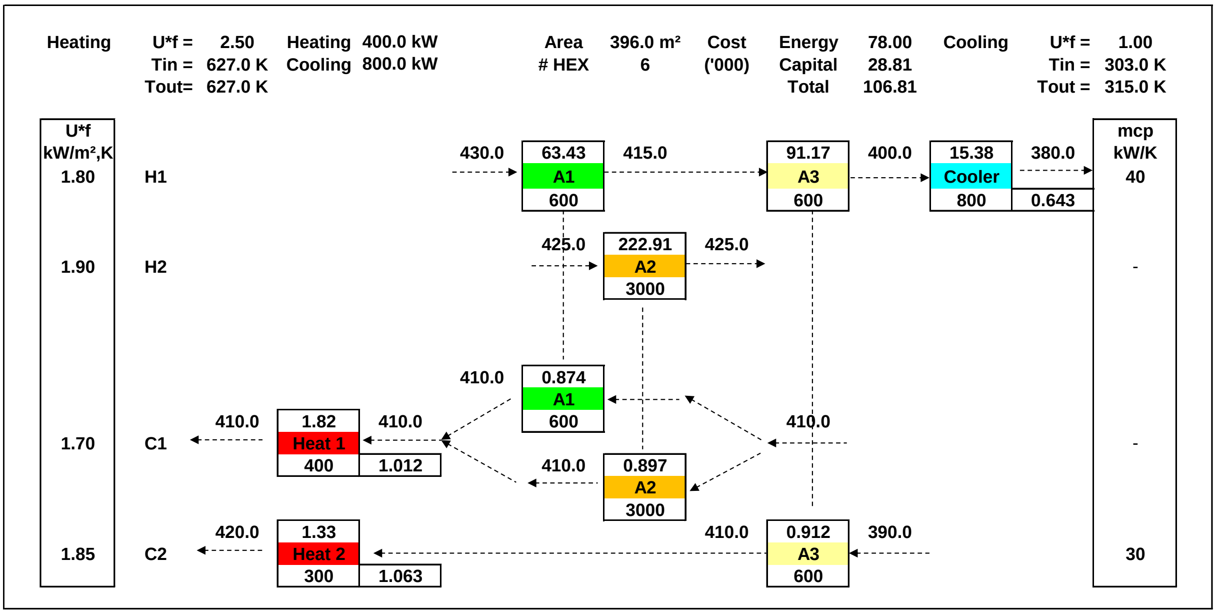


Figure 5.2

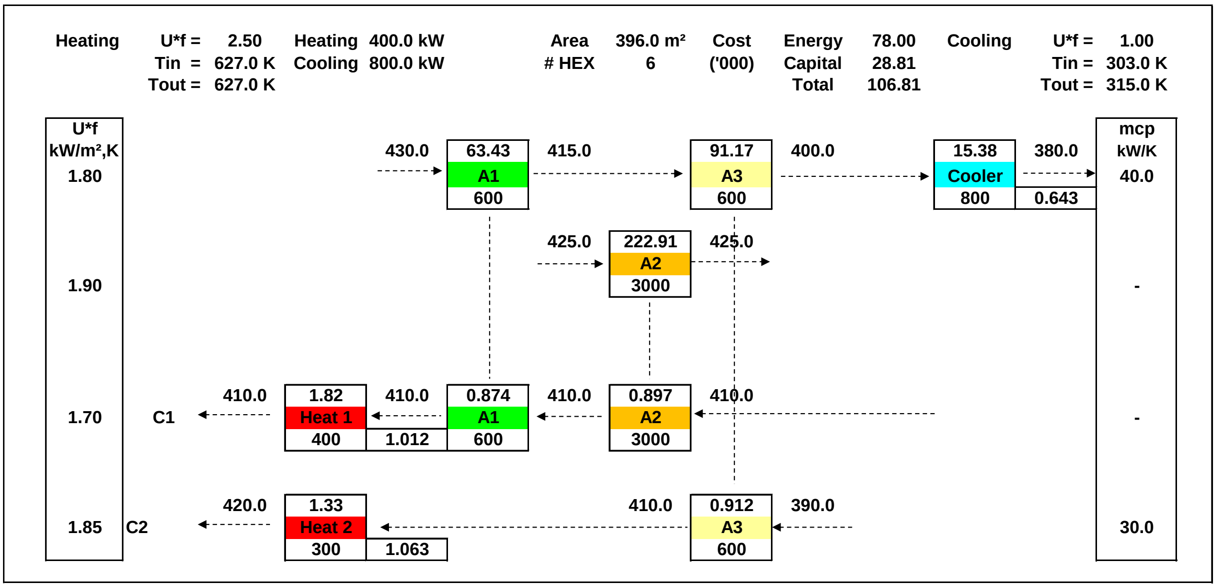


Figure 5.3

5.2 The 7-streams problem (3H4C).

The data set for the second problem has 3 hot streams and 4 cold streams and is shown in Table 5.2 for an overall DTMin of 5 K. It was originally developed by Ponce-Ortega et al. [44]. In that study, heat exchanger cost was set at 379.5 x Area$^{0.65}$ \$/year. It was also studied by Cerda et al. [40], Aguitoni et al. [45] and by Xiao et al. [46].

The pinch is caused by cold stream C4. The trade-off curve in Figure 5.4 would suggest a heat load of 4900 kW; in such case, however, the minimum DeltaT of 5 K would not be achievable.

A network developed with pinch design rules, requesting one single heater, is identical with the network developed with SYNHEAT except that it shows no stream splits, which could be avoided by appropriate sequencing of condensers and evaporators and is shown in Figure 5.5. It has a cost of 683.60 \$/year. Alternatively, also a network with 2 heaters and 10 units was developed, as shown in Figure 5.6; the cost of that network is 683.83 k\$/year and only 0.0325% higher than the network with 1 heater. The results can be compared in Table 5.3. Some published networks had to be reviewed.

Table 5.2

	Tsupply	Ttarget	Heat	Shift	U*f	Description
	K	K	kW	K	kW/m²,K	-
	503.0	308.0	12948.0	2.5	0.81	H1
	425.0	424.9	33020.0	2.5	1.78	H2
	381.0	380.9	12870.0	2.5	1.62	H3
	323.0	503.0	8838.0	2.5	0.72	C1
	408.0	408.1	18413.1	2.5	1.91	C2
	391.0	391.1	18498.4	2.5	1.76	C3
	353.0	353.1	16347.9	2.5	1.84	C4
	627.0	626.9	5106.4		2.50	Heating
	303.0	315.0	1847.0		1.00	Cooling

Cost data

Heating : 100.0 \$/kW,year   Cooling : 10.0 \$/kW,year

HEX cost : 380 x Area$^{0.65}$ \$/year

Table 5.3

	Heating	Area	units	splits	Cost
	kW	m²	#	#	'000 $/y
Poncé Ortega et al.	5106.4	3606.2	9	0	686.52
Aguitoni (2 Heaters, non-iso)	5106.4	3593.0	10	1	687.56
Xiao et al. 1°)	5106.4	3590.2	9	0	688.22
Cerda et al. 2°)	5106.4	3606.2	9	0	686.52
SYNHEAT 2°)	5106.4	3482.5	9	0	683.60
This study					
1 Heater	5106.4	3482.5	9	0	683.60
2 Heaters	5106.4	3483.2	10	0	683.83

1°) Network with DTMin of 1.67 K, adjusted for 5 K

2°) Cost reviewed by the author

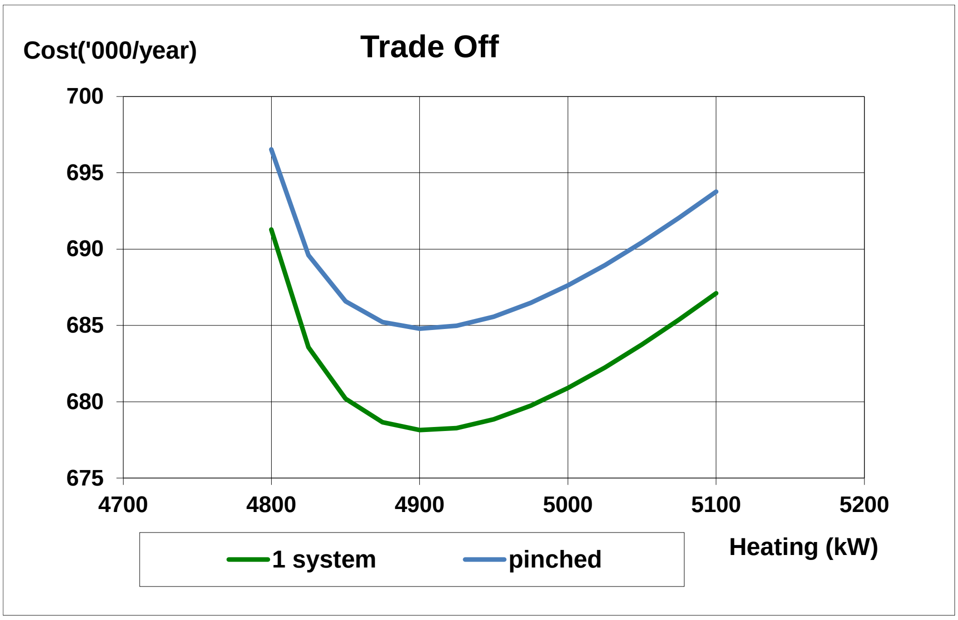


Figure 5.4

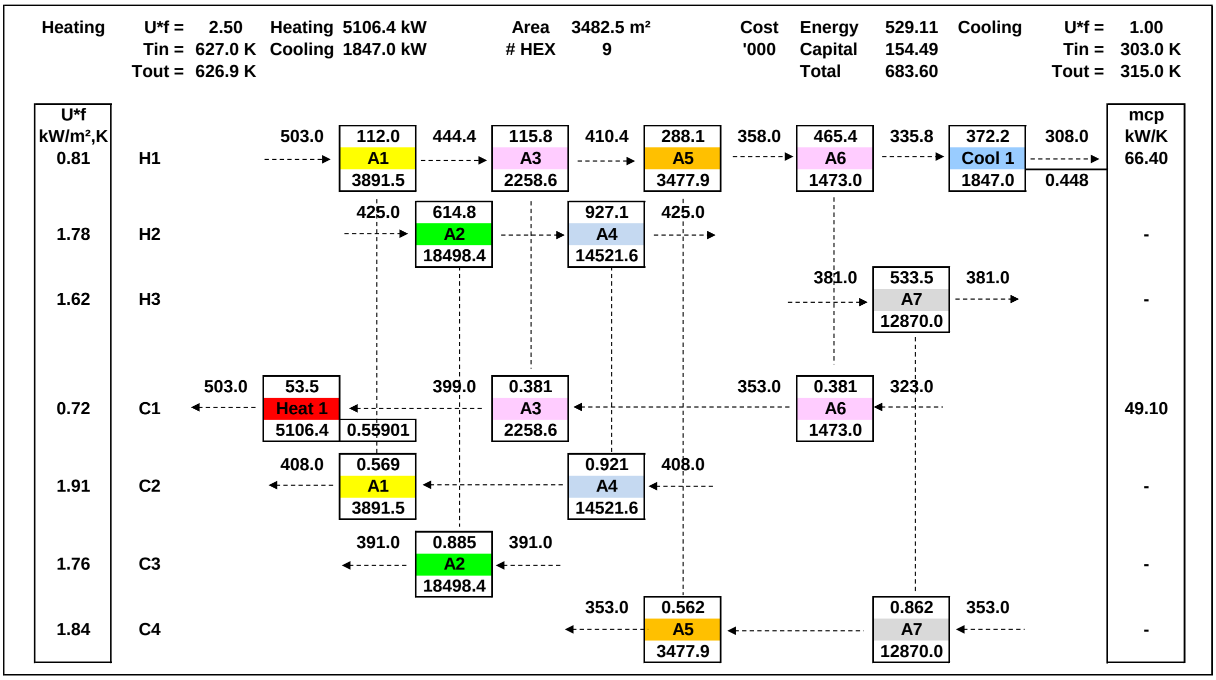


Figure 5.5

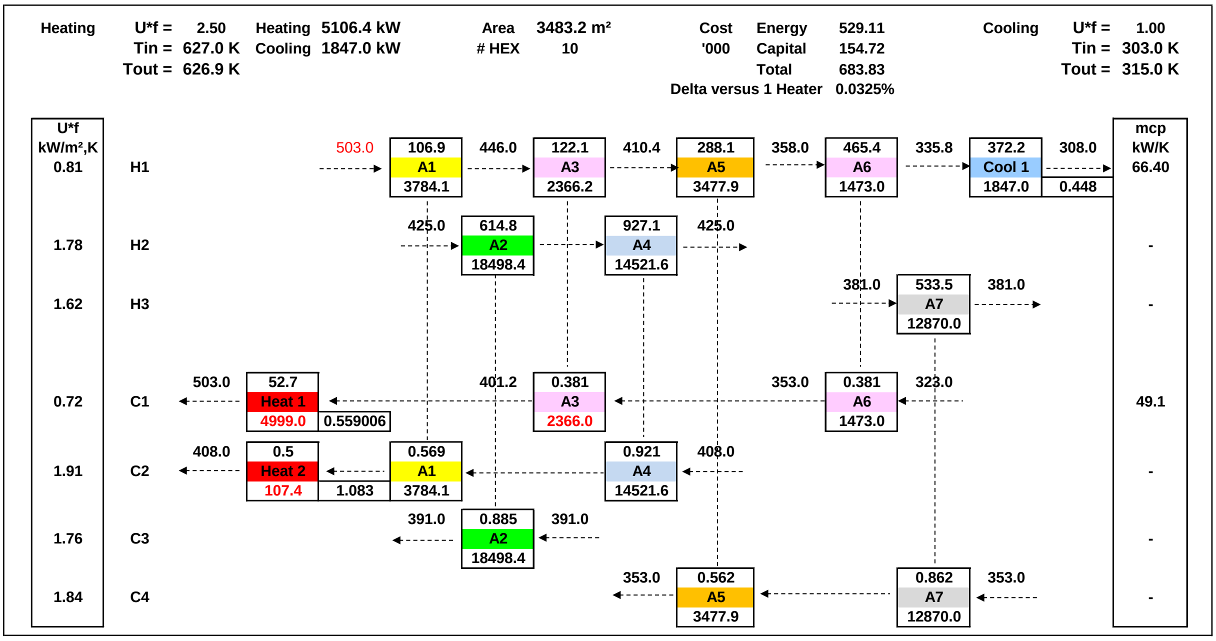


Figure 5.6

5.3 The 7-streams problem (4H3C).

The dataset for this problem has 4 hot streams and 3 cold streams and is shown in Table 5.3 for a DTMin of 5 K. This problem was originally from Ponce-Ortega et al. [44] and has also been studied by Cerda et al. [40].

Composite curves are shown in Figure 5.7. Heating requirements of 1068.7 kW are constant up to a DTMin of 15 K. The Grand Composite is shown in Figure 5.8.

The network obtained with SYNHEAT (Baron) is shown in Figure 5.9. It has a cost of 156.33 k$/year. The network applying pinch design rules is shown in Figure 5.10. It has a cost of 155.97 k$/year. The structure is identical with the network developed by Ponce-Ortega et al. [44] and Cerdá et al. [40].

The shape of the Grand Composite would incite the study of incorporation of a heat pump, recovering heat from hot stream H1 and pumping it up for use on cold stream C1. The resulting network is shown in Figure 5.11. The heating requirement would be reduced from 1068.7 kW to 76.2 kW, the cooling requirement from 1900.0 kW to 982.1 kW.

The following additional data and assumptions were used for the evaluation:

- Compressor capacity: 90 kW, load 89.4 kW
- Heat pump compressor efficiency: 75%
- Drive efficiency: 90%
- Subcooling of condensate from heat pump: 50 kW (ca. 5% of condensed heat).

The resulting heat pump COP would be 12.2. Financial assumptions are:

- Power cost: 4 x cost of hot utility
- Investment cost heat pump (90 kW-motor, VSD and compressor): 90 k$, annuity 25%.

The cost of the network with a heat pump is 112.41 k$/year. Results can be compared in Table 5.4.

Table 5.3

Tsupply	Ttarget	Heat	Shift	U*f	Description
K	K	kW	K	kW/m²,K	-
340.0	339.9	1900.0	2.5	1.52	H1
390.0	389.9	1493.1	2.5	1.63	H2
420.0	419.9	2594.4	2.5	1.75	H3
475.0	474.9	1999.1	2.5	1.58	H4
350.0	350.1	992.5	2.5	1.81	C1
375.0	375.1	1801.2	2.5	1.72	C2
400.0	400.1	4361.6	2.5	1.64	C3
627.0	626.9	1068.7		2.50	Heating
303.0	315.0	1900.0		1.00	Cooling

Cost data

Heating : 100.0 \$/kW,year   Cooling : 10.0 \$/kW,year

HEX cost : 380 x Area$^{0.65}$ \$/year

Table 5.4

	Heating	Area	units	splits	Cost
	kW	m²	#	#	'000 \$/y
Ponce-Ortega	1068.7	319.3	7	-	155.97
Ziyatdinov (SYNHEAT)	1068.7	356.8	7	-	156.33
Cerdá et al.	1068.7	319.3	7	-	155.97
This study					
Conventional	1068.7	319.3	7	-	155.97
With heat pump	76.2	469.1	7	1	112.41

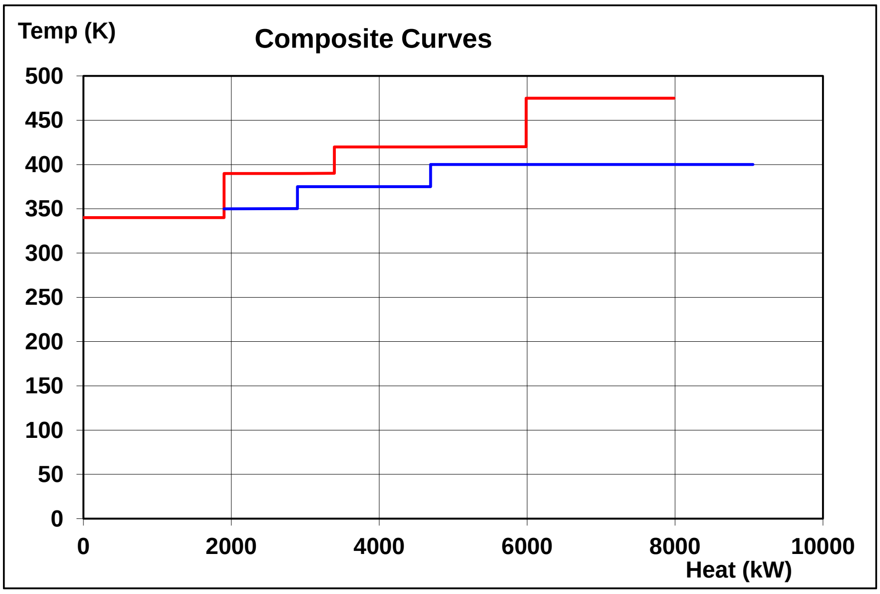


Figure 5.7

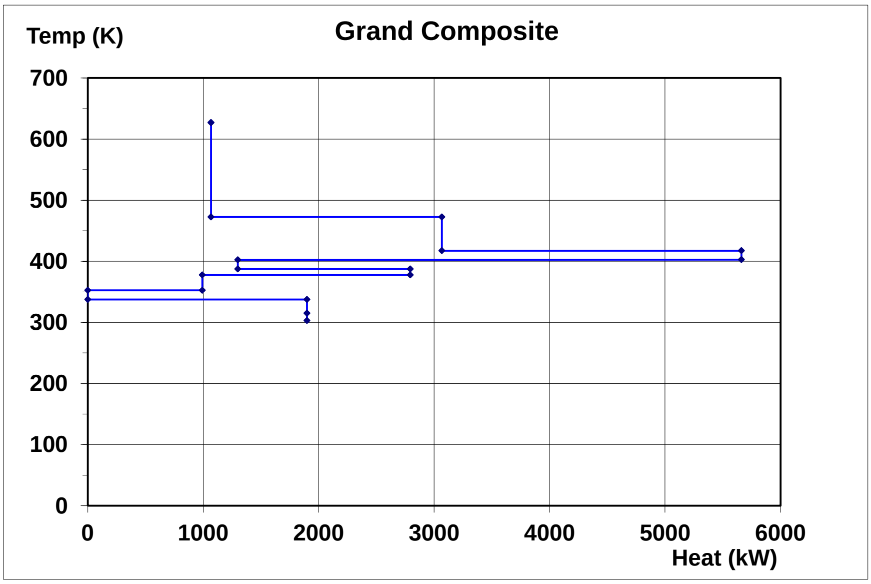


Figure 5.8

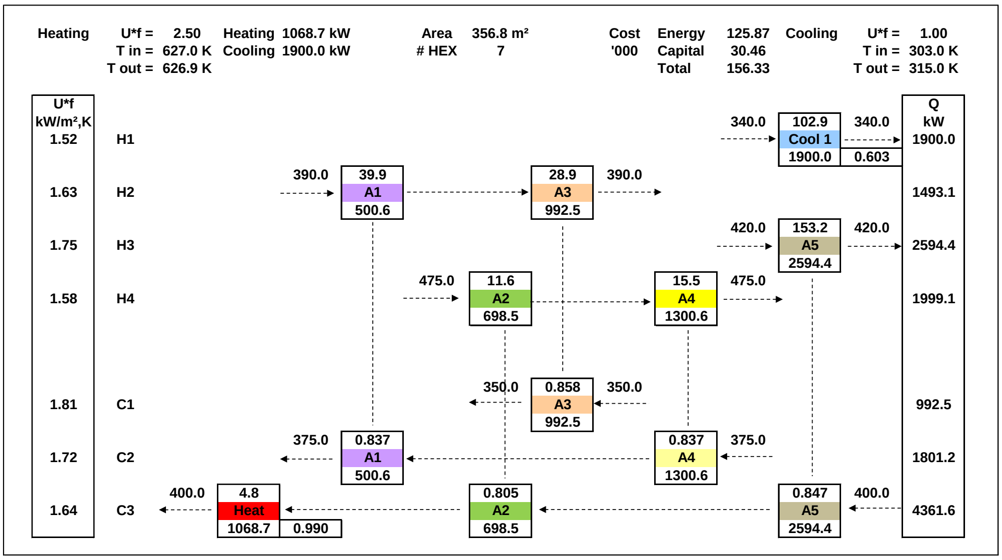


Figure 5.9

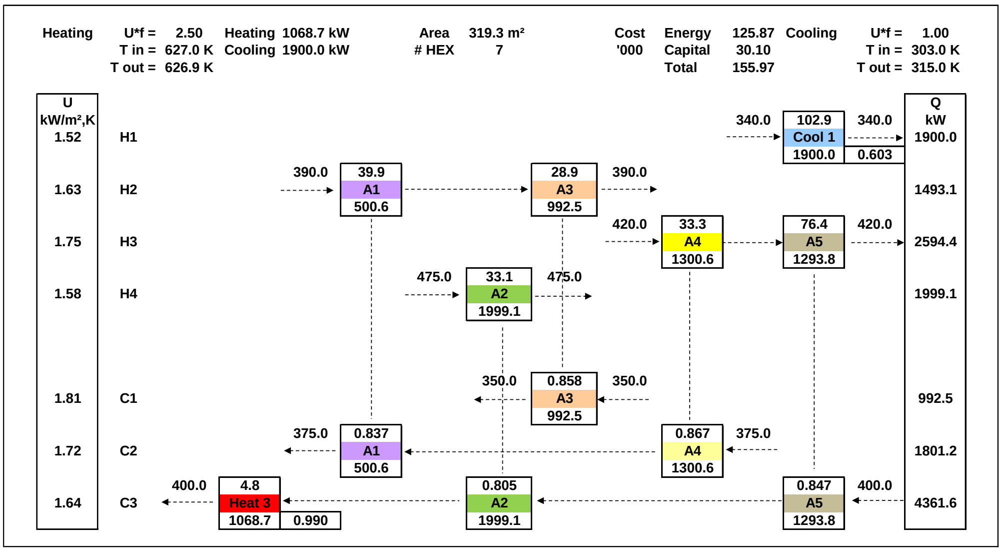


Figure 5.10

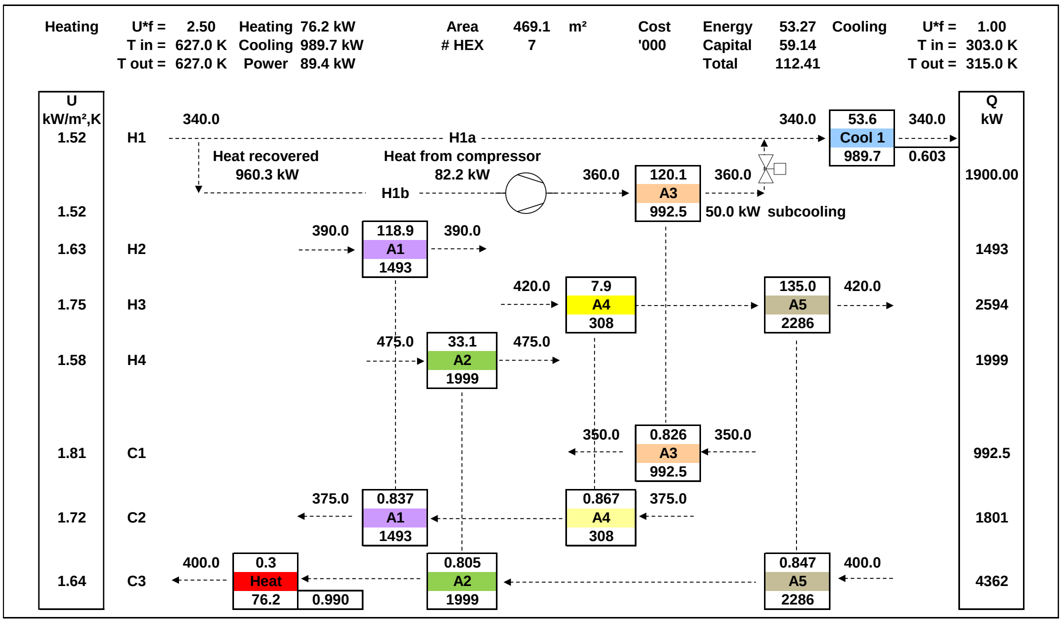


Figure 5.11

5.4 The 8-streams problem (4H4C).

The dataset for the fourth problem has 4 hot streams and 4 cold streams and is shown in Table 5.5 for a DTMin of 10 K. Trade-off between energy and capital would drive the system into a threshold problem with a DTMin of 4.625 K and no heating as shown in Figure 5.12.

First, the analysis was made with an EMAT of 10 K. The pinch is caused by hot stream H1. The cost target is between 435.04 k$/year for a network with 9 units (1 system) and 447.07 k$/year for a network with 12 units (pinched network). The network obtained by SYNHEAT is shown in Figure 5.13. It has 12 units, 4 splits, an area of 3384.1 m² and has a cost of 435.96 $/year. A network developed by applying pinch design rules with the tick-off procedure is shown in Figure 5.14. It has 12 units, 2 splits, an area of 3270.5 m² and has a marginally lower cost of 433.89 k$/year. A network with 1 split is shown in Figure 5.15; it has a cost of 434.34 k$/year.

Then, the analysis was made for the threshold problem, assuming an EMAT of 4K. A network with 12 units is shown in Figure 5.16, one with 11 units in Figure 5.17. Their cost is marginally lower than that of the network from Cerda et al. All networks were designed using the tick-off procedure. Only networks with iso-thermal splits were considered. The results can be compared in Table 5.6.

Table 5.5

Tsupply	Ttarget	Heat	Shift	U*f	Description
K	K	kW	K	kW/m²,K	-
420.0	360.0	3000	5.0	1.00	H1
470.0	375.0	19000	5.0	2.50	H2
485.0	390.0	14250	5.0	2.00	H3
500.0	435.0	6500	5.0	2.00	H4
340.0	380.0	2400	5.0	1.00	C1
365.0	430.0	7800	5.0	1.00	C2
395.0	450.0	5500	5.0	1.00	C3
410.0	465.0	22000	5.0	1.00	C4
620.0	619.9	2150		5.00	Heating
300.0	315.0	7200		1.00	Cooling

Cost data

Heating : 85.0 $/kW,year   Cooling : 15.0 $/kW,year

HEX cost : 380 x Area$^{0.65}$ $/year

Table 5.6	Heating	Area	units	splits	Cost
EMAT 10K	kW	m²	#	#	'000 $/y
Ziyatdinov (SYNHEAT) 1°)	2150	3384.1	12	4	435.96
Cerda et al. 1°)	2150	3436.5	12	1	438.20
This study					
Pinch design procedure - tick-off	2150	3270.5	12	2	433.89
	2150	3275.2	12	1	434.34
EMAT 4K					
Cerda et al.	0	5359.7	11	1	274.41
This study					
Pinch design procedure - tick-off	0	5566.3	12	1	273.39
	0.0	5254.5	11	1	274.00

1°) Revised by the author

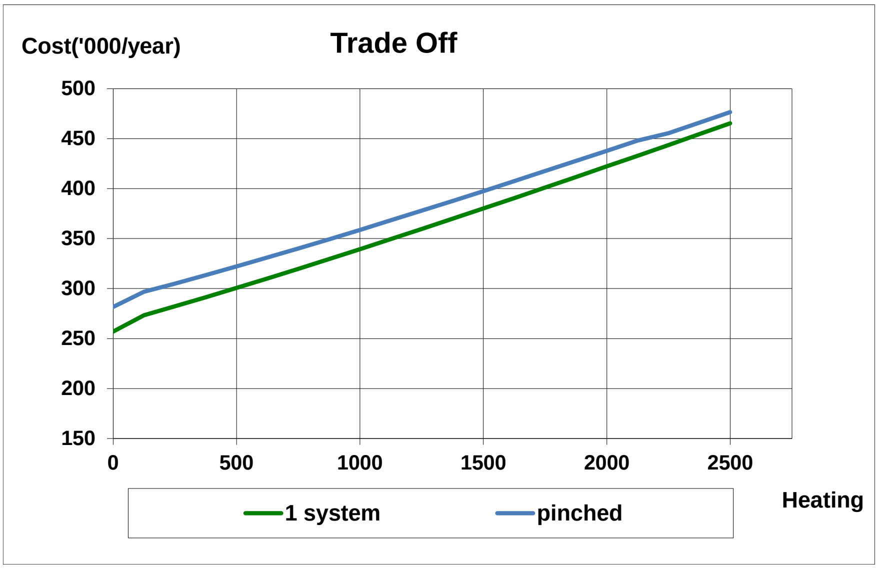


Figure 5.12

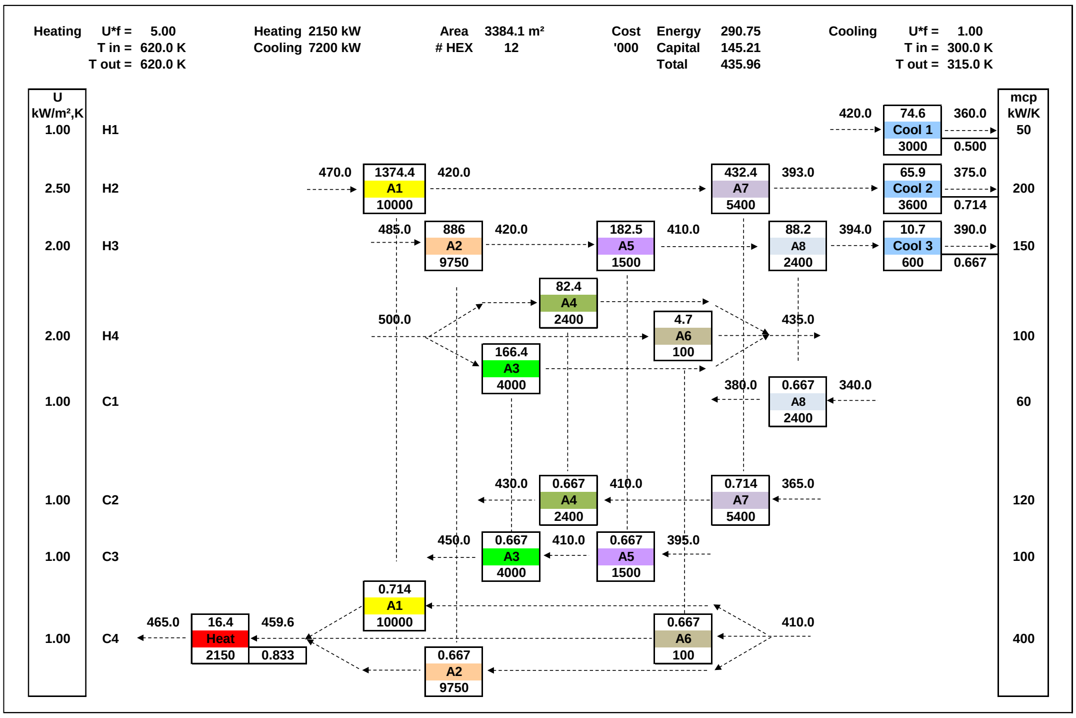


Figure 5.13

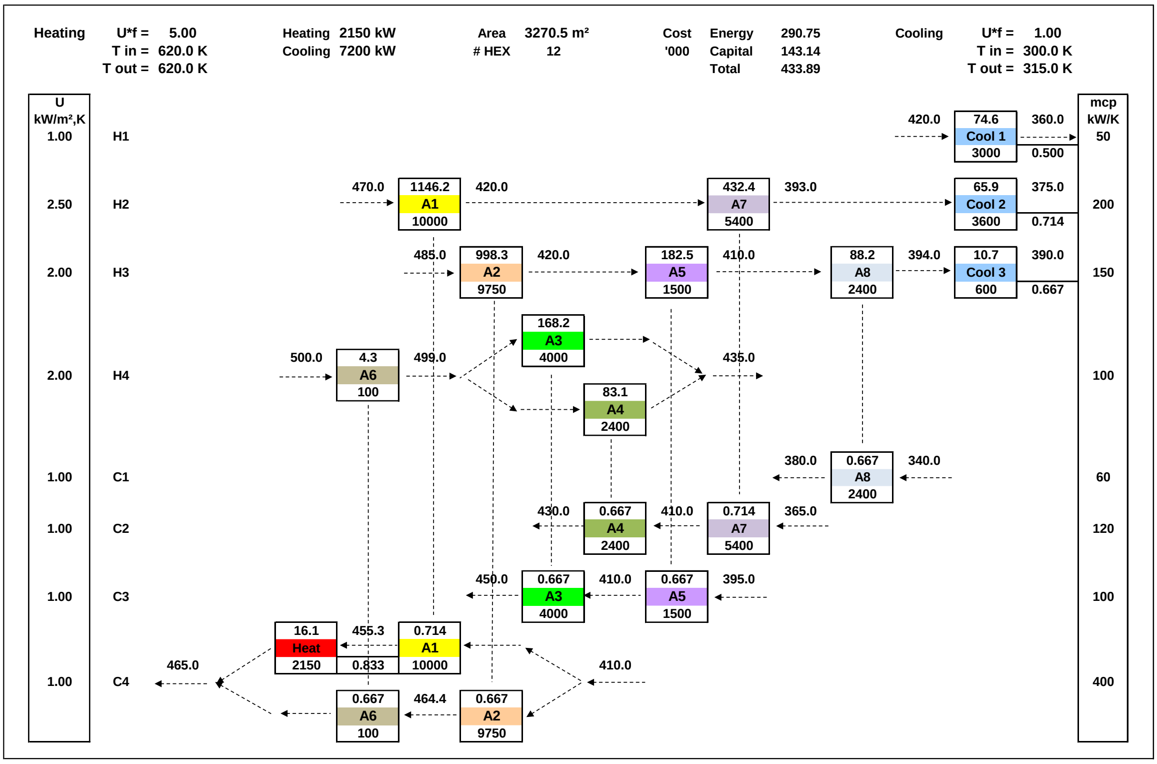


Figure 5.14

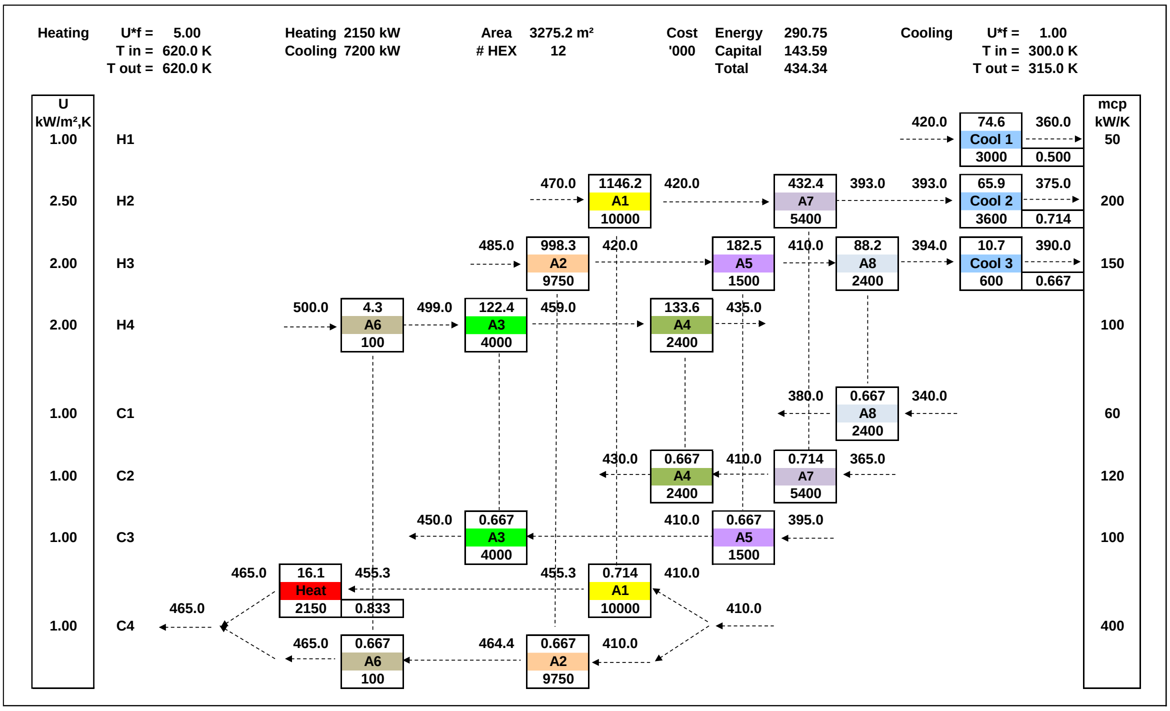


Figure 5.15

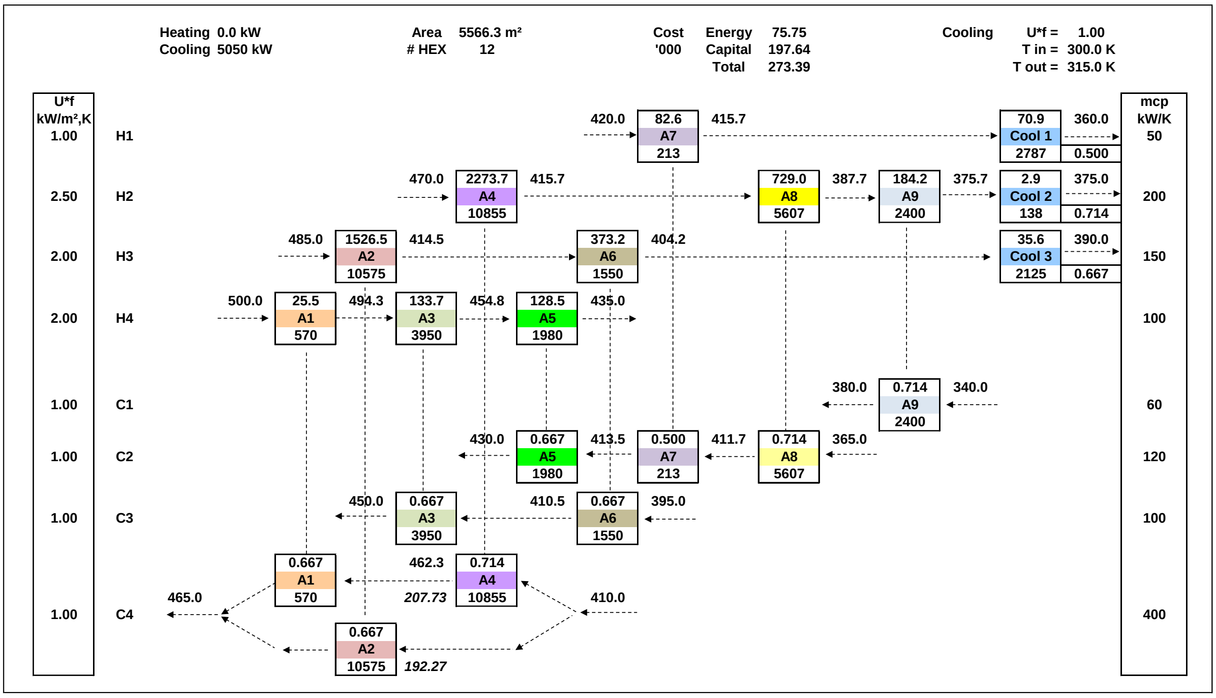


Figure 5.16

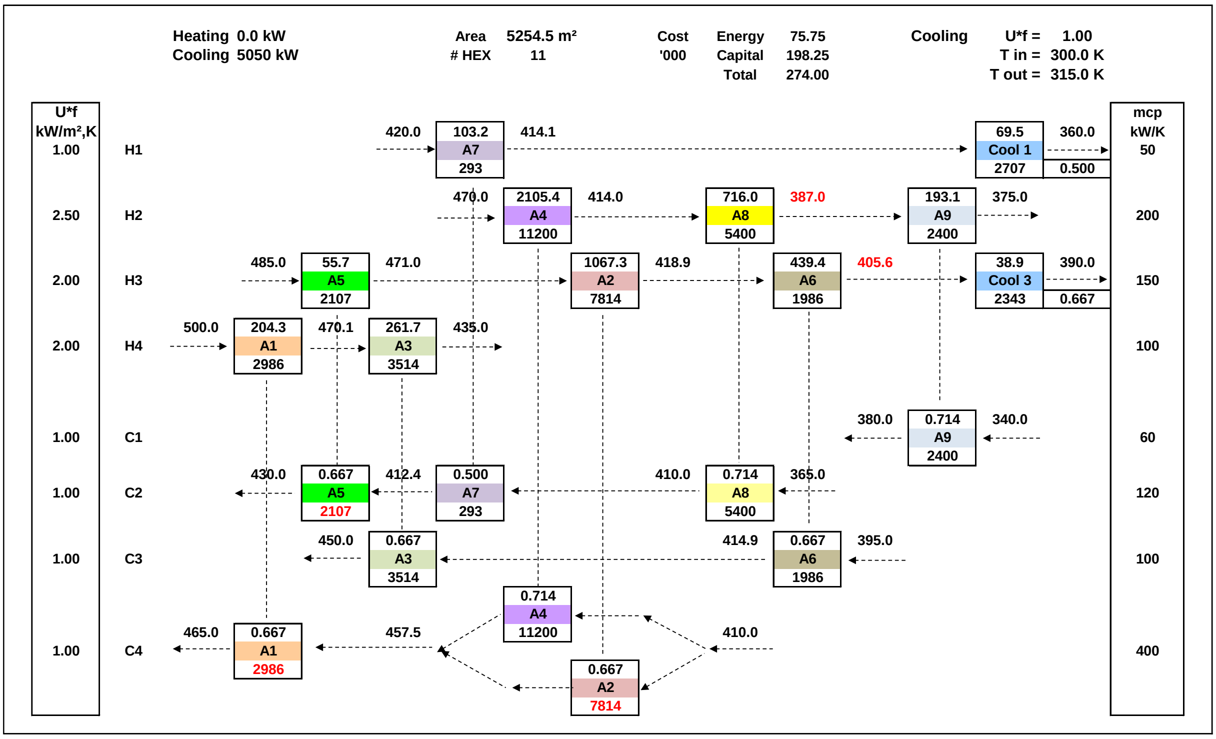


Figure 5.17

6 Comparison of methods: a (3H3C) problem.

A specific problem in synthesising heat exchanger networks is the handling of different heat transfer coefficients. In the Pinch Technology method, this can be taken care of in the analysis stage by allocation of stream-specific DTMin contributions. Several authors have proposed shifting procedures using formula relating said contributions to the stream specific heat transfer coefficients. It has been demonstrated, however, that a simple relation does not exist (see [47]).

The Pinch Technology based Supertarget procedure was combined with the Area Targeting Model (ATM) using shifting procedures mentioned above, leading to Hypertargets [48]. This development has already been compared with Crisscross Optimisation prior to design in [49]. The study of Example 1 in [48] with 3 hot streams and 3 cold streams has been further elaborated, accounting for Ft-factors, linked to Shell-and-Tube heat exchangers.

Stream data and cost parameters are given in Table 6.1.

Table 6.1

Tsupply	Ttarget	Heat	Shift	Shift	U*f	Description	mcp
			ATM	Crisscross			
°C	°C	kW	K	K	kW/m²,K	-	kW/K
150	60	1800	18.67	17	0.05	H1	20
90	60	2400	6.60	0	0.40	H2	80
181	180	1075	4.17	0	1.00	H3	1075
20	125	2625	13.20	11	0.10	C1	25
25	100	2250	5.39	0	0.60	C2	30
10	15	400.0	5.39	0	0.60	C3	80
200	199				4.00	Heating	-
10	15				1.00	Cooling	-

Cost data

Heating: 130 $/kW,year Cooling: 30 $/kW,year

HEX Cost ($): 8600 + 670 x Area$^{0.83}$

Life time: 10 years Discount rate: 15%

In Table 6.1, also the stream-specific shift values, used in the Area Targeting Model are given as well as the results of the Crisscross Optimisation procedure for the threshold situation. Composite Curves are shown in Figure 6.1, the pinch is caused by hot stream H2. The Trade-off curve is shown in Figure 6.2. The system is fully balanced, no heating nor cooling is required.

The network synthesis was first done assuming counter-current heat exchange as in the referenced paper [48]. The result of the published network was revised for an area, calculated with correct LnMTD. That network is shown in Figure 6.3. In this study, networks were developed with 6 units, shown in Figure 6.4 and with 5 units, shown in Figure 6.5. Then, the synthesis was continued, assuming Shell-and-Tube heat exchangers. The result for the network from Briones et all. is shown in Figure 6.6. The networks developed in this study are shown in Figure 6.7 for a network with 6 units, respectively in Figure 6.8 for a network with 5 units. The results are summarised in Table 6.2.

The procedure with Crisscross Optimisation Prior to Design combined with smart optimisation procedures is clearly superior to the much more complicated procedure of Hypertargets.

Table 6.2	Area	Units	Shells	Cost
	m^2	#	#	'000 $/y
w/o Ft				
Briones et all. °1)	3319.4	5	-	702.0
This study	1972.3	6	-	486.7
	2106.0	5	-	525.7
°1) revised with area calculation with LnMTD				
with Ft				
Briones et all. °2)	3660.1	5	10	914.2
This study	2132.2	6	10	594.6
	2321.0	5	7	613.1
°2) results from Briones et all. adjusted with Ft correction				

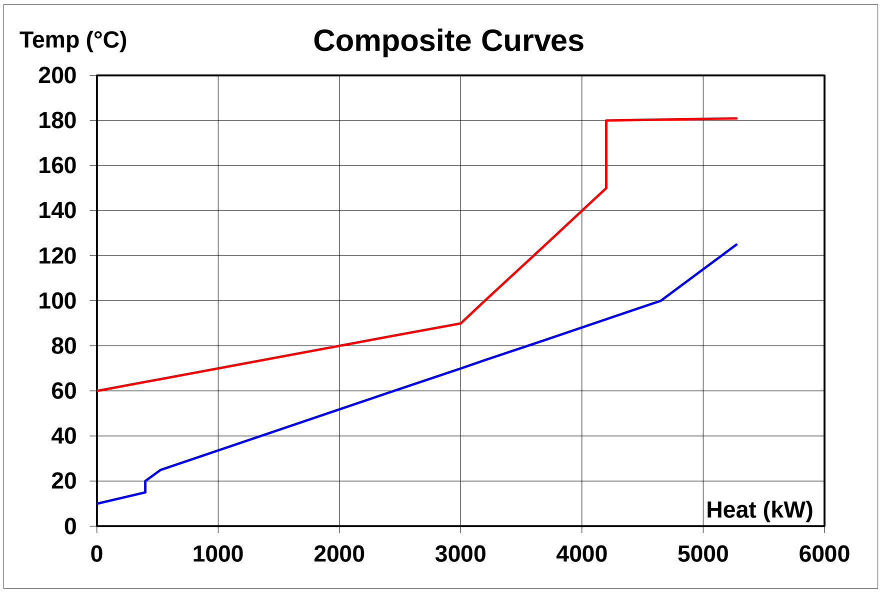


Figure 6.1

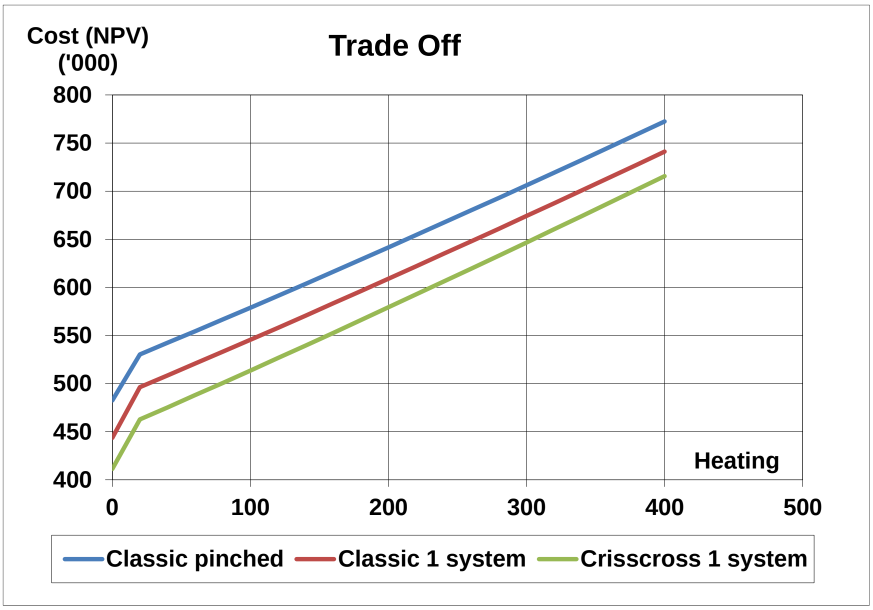


Figure 6.2

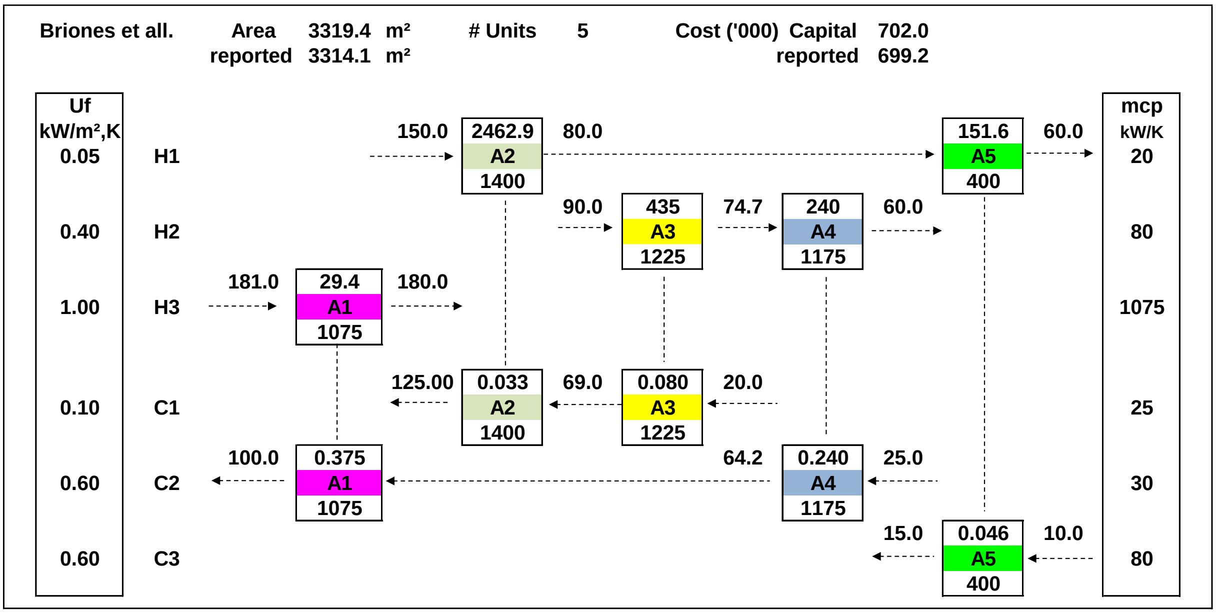


Figure 6.3

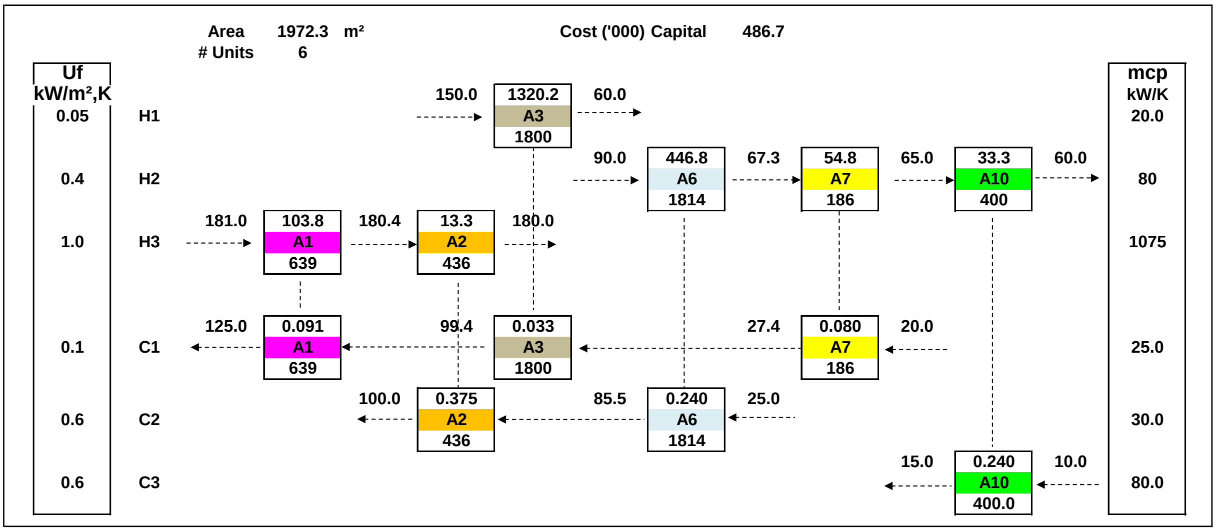


Figure 6.4

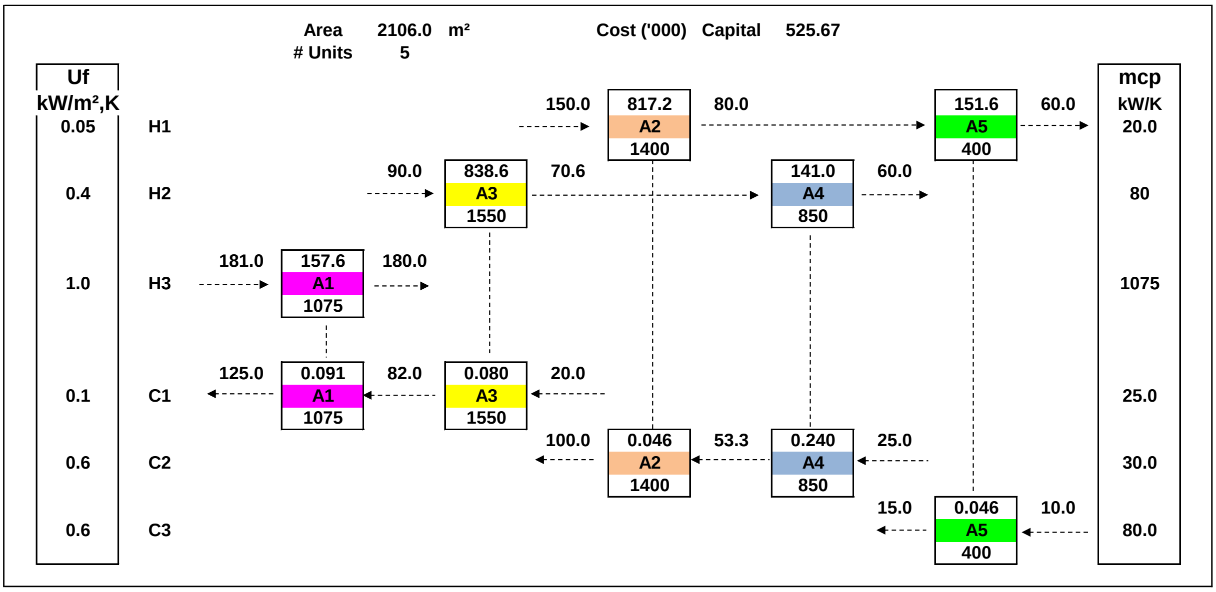


Figure 6.5

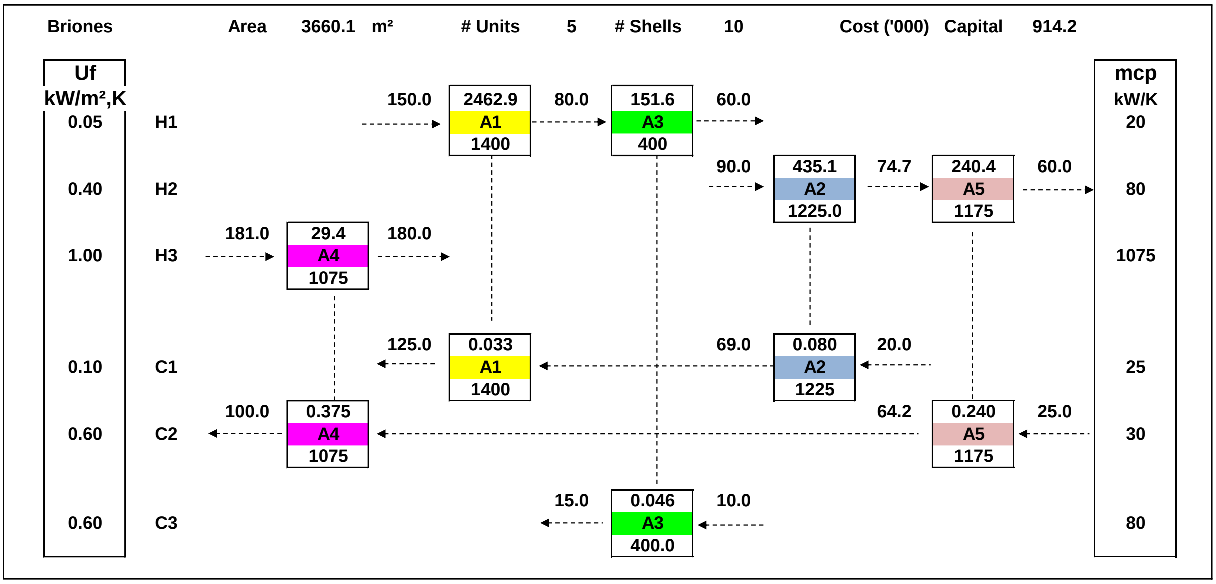


Figure 6.6

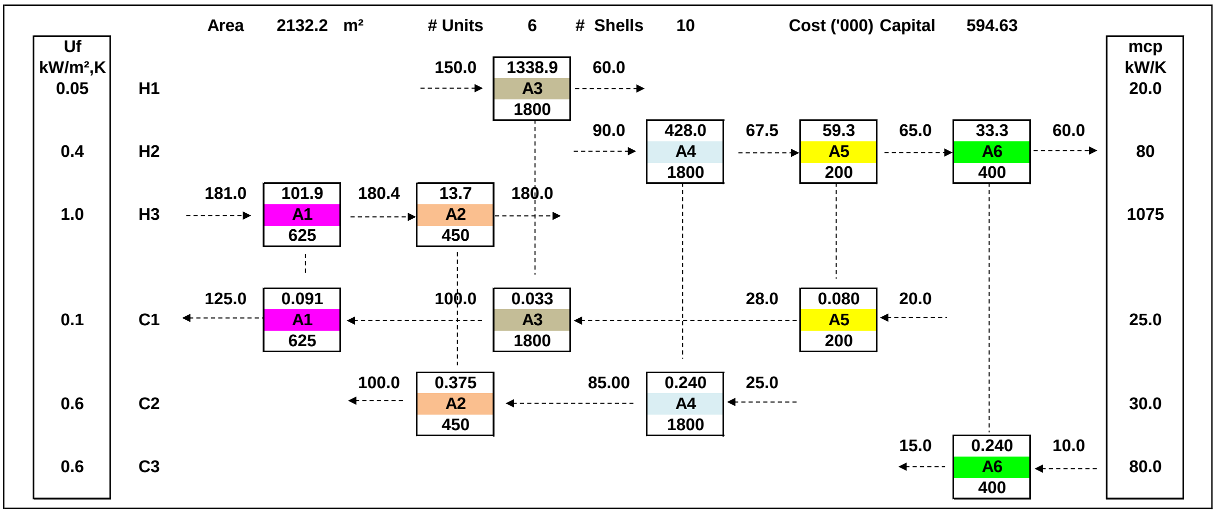


Figure 6.7

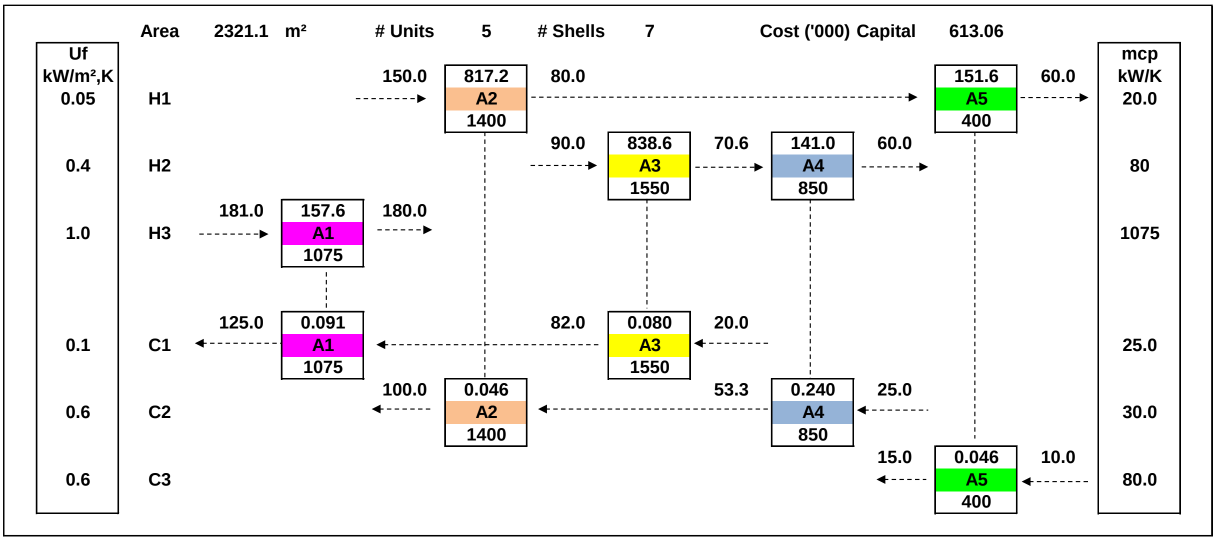


Figure 6.8

7 The 4H3C problem from Ciric & Floudas

This problem with 4 hot streams and 3 cold streams was taken from Ciric et Floudas [50]. It was also studied by Chen et al. [51], by Huang and Karimi [52] and by Cerda et al. [40]. It was studied by Trivedi et al., however, with a different heat load for hot stream H4 and, therefore, not comparable with other studies.

The data set is shown in Table 7.1.

Table 7.1

Tsupply °C	Ttarget °C	Heat kW	Shift K	U*f kW/m²,K	Description -
160	110	351.60	7.45	1.60	H1
249	138	936.84	7.45	1.60	H2
227	106	1429.74	7.45	1.60	H3
271	146	875.00	7.45	1.60	H4
96	160	585.22	7.45	1.60	C1
115	217	744.19	7.45	1.60	C2
140	250	1980.00	7.45	1.60	C3
300	300	230.00		1.60	Heating
70	90	513.77		1.60	Cooling

Cost data

Heating : 80.0 $/kW,year Cooling : 20 $/kW,year

HEX cost = 1300 x $A^{0.6}$ $/year

This problem has several specific features.

The Composite Curves are quasi parallel in a large integration band as shown in Figure 7.1. The heating load in Table 7.1 was chosen from the trade-off analysis shown in Figure 7.2 which shows a minimum for a network with one single system and 8 heat exchanger units. Depending upon the choice of the pinch location, either 11, 12 or 13 units would be required. There are multiple pinches in the system as shown in the driving force diagram in Figure 7.3 for a DTMin of 14.27 K: hot stream H3 and cold stream C3 are both causing the pinch, whilst hot stream H1 causes a near pinch with a margin of less than 0.9 kW.

The pinch analysis generates a grid with 13 integration bands; application of LP to that grid generates a network with 39 units. For reducing the number of units in the initial network, the number of integration bands can be reduced to a figure between 13 and 3, indicating a lot of potential initial networks. Using incremental evolution, many initial networks evolve into the near optimum network of Figure 7.4 with a cost of 105.77 k$/year.

A particular initial network evolved into the final network of Figure 7.5 with a cost of 111.70 k$/year. Another network with a cost of 105.48 k$/year is shown in Figure 7.6. Remarkably, moving heat exchanger A2 in the network of Figure 7.5 into the spilt of cold stream C3 results in the network of Figure 7.6. During the evolution process, the network of Figure 7.7 with 12 units was found. The split in the red encircled area was developed into a smart split as shown in Figure 7.8. Further incremental evolution led to the optimum network of Figure 7.9 with a cost of 105.42 k$/year. Remarkably, again, moving the Heater in the network of Figure 7.6 into the spilt of cold stream C3 would result in the network of Figure 7.9.

An alternative approach is based on heuristics.

For achieving the minimum number of units in a single independent system, each exchanger must tick off either a process stream or a utility requirement. The following queries are useful:

- Check whether the smallest (or a small) stream can be ticked off with a partner with minimum violation of pinch design rules.
- Check whether matches are possible between streams with comparable mcp's in parallel sections of the composite curves.
- Check whether matches are possible between streams that cover the same integration span.
- Check whether matches are possible between streams crossing the pinch with minimum violation of pinch design rules.

Analysis of the grid and the location of the pinch leads to the following possible matches:

- H4 on a branch of C3 (comparable integration span).
- H1 on Cooling (H1 is below or mainly below the pinch).
- Since the cooling requirement would not be satisfied with the cooler on hot stream H1, remaining cooling requirement shall be put on hot stream H3.

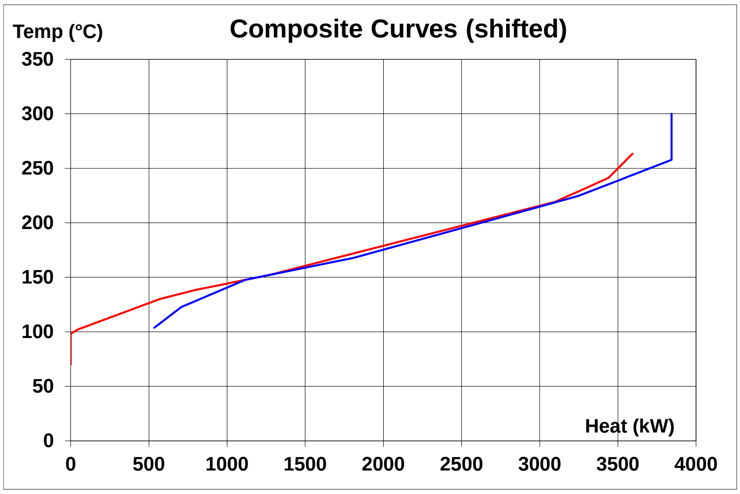
Accepting the first match suffices to synthesize the optimum network using LP. Accepting the 3 matches enables synthesis of the optimum network by hand.

The optimum network has also been developed by Huang et al. [52], with much more complicated procedures, however. Some studies have used a supply temperature of 115°C for cold stream C2, others have used 116°C. All calculations have been adjusted for a temperature of 116°C. Other small differences in the results might be caused by rounding errors.

The results are summarized in Table 7.2.

Table 7.2	Heating	Area	units	splits	Cost
	kW	m²	#	#	'000 $/y
Ciric et all.	175.4	280.8	12	2	114.32
Chen et al.	249.7	266.8	8	2	105.79
Huang et all. °)	211.8	274.4	8	1	105.42
°) revised by the author					
This research	303.8	244.3	8	1	111.70
	247.9	268.4	8	2	105.77
	213.8	272.5	8	1	105.48
	211.9	274.3	8	1	105.42

Figure 7.1



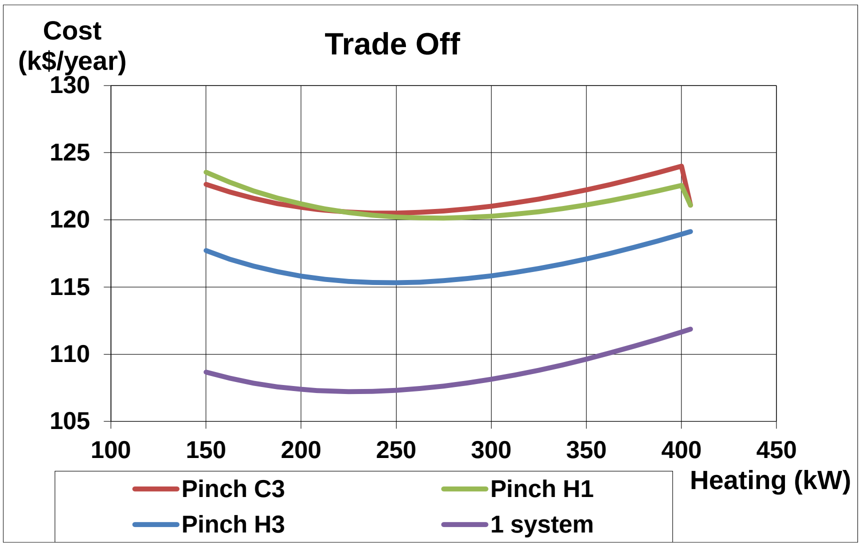


Figure 7.2

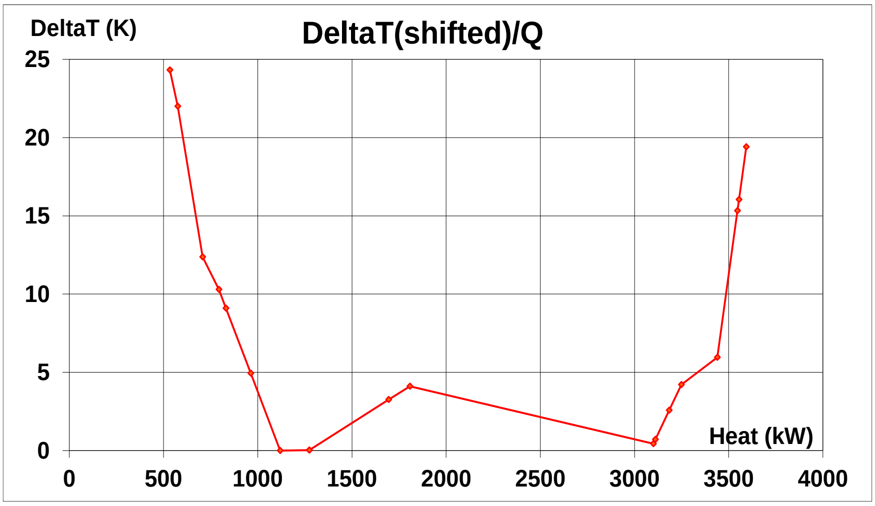


Figure 7.3

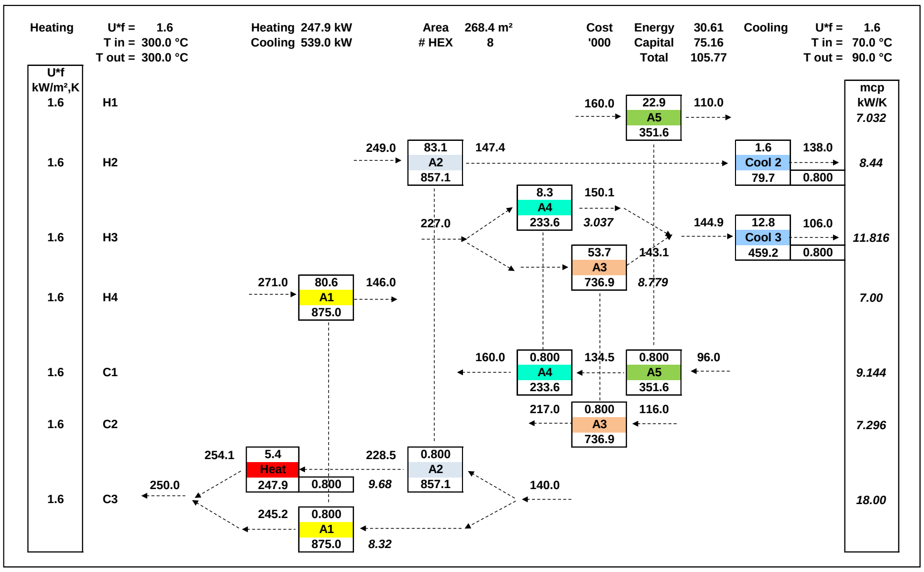


Figure 7.4

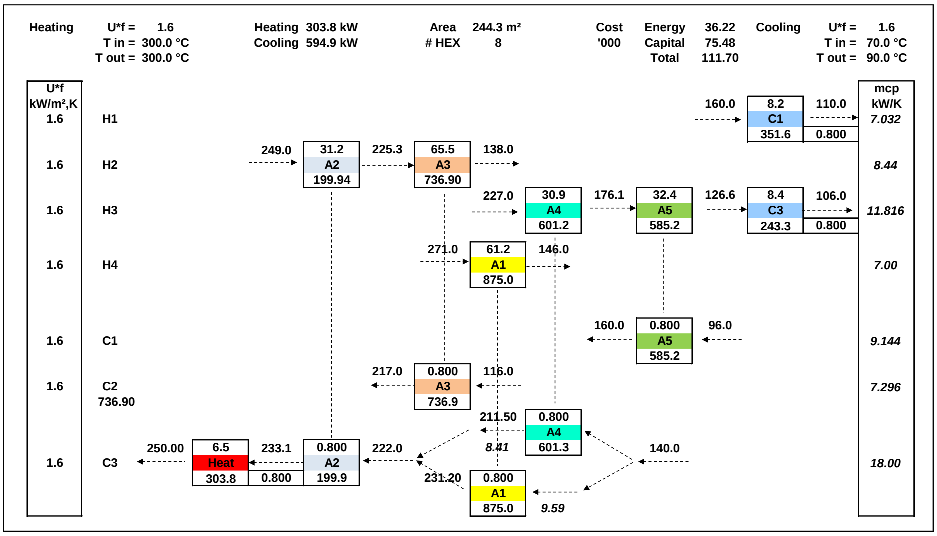


Figure 7.5

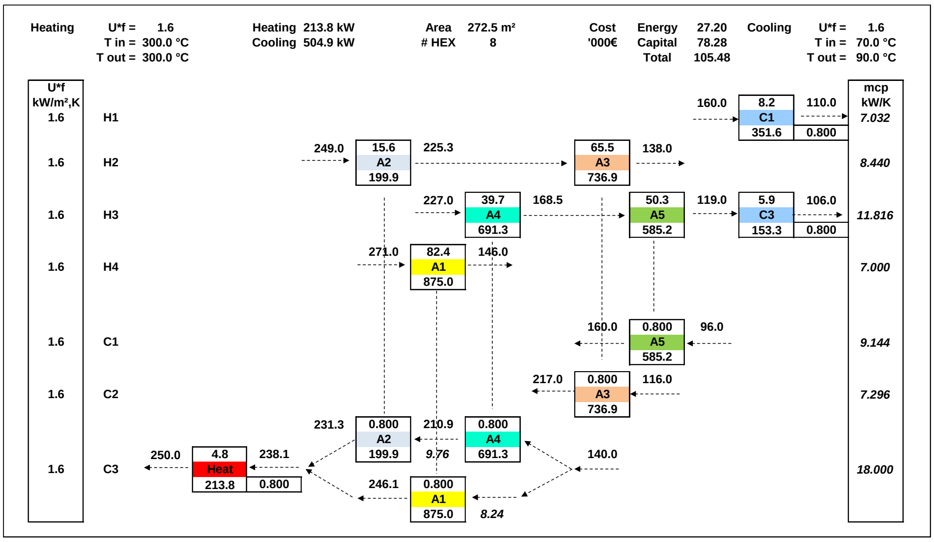


Figure 7.6

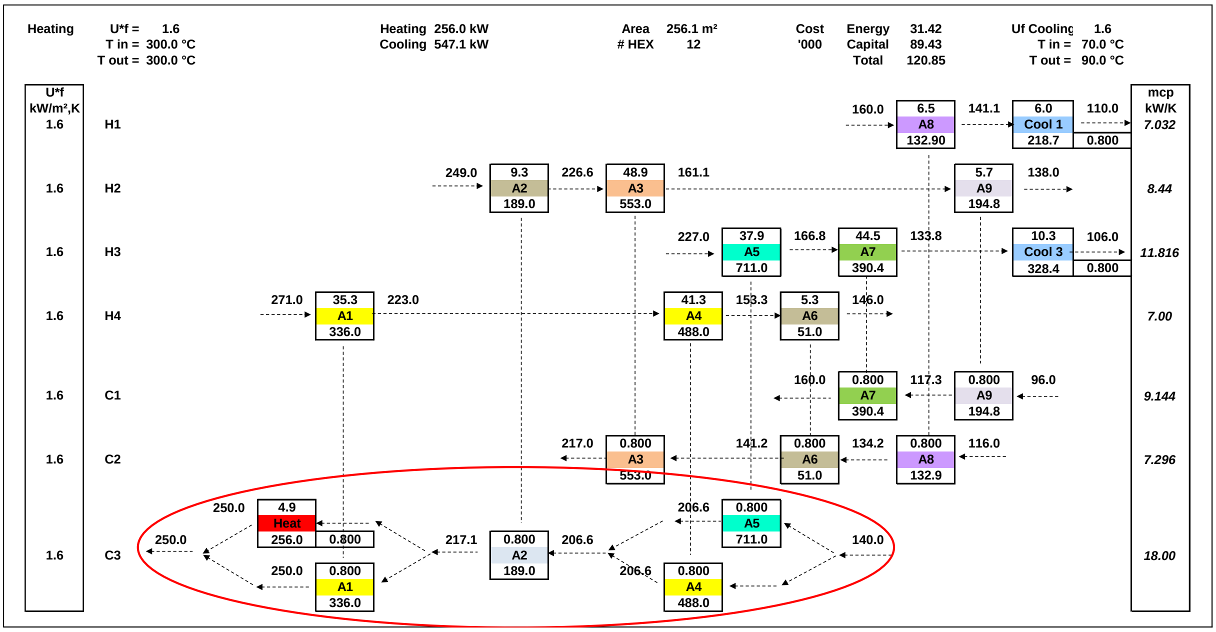


Figure 7.7

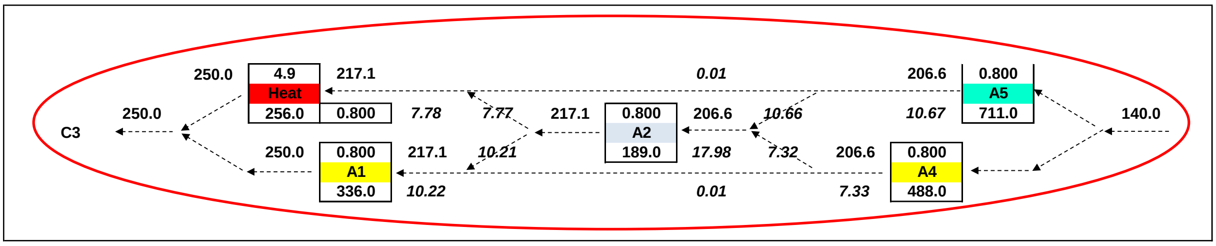


Figure 7.8

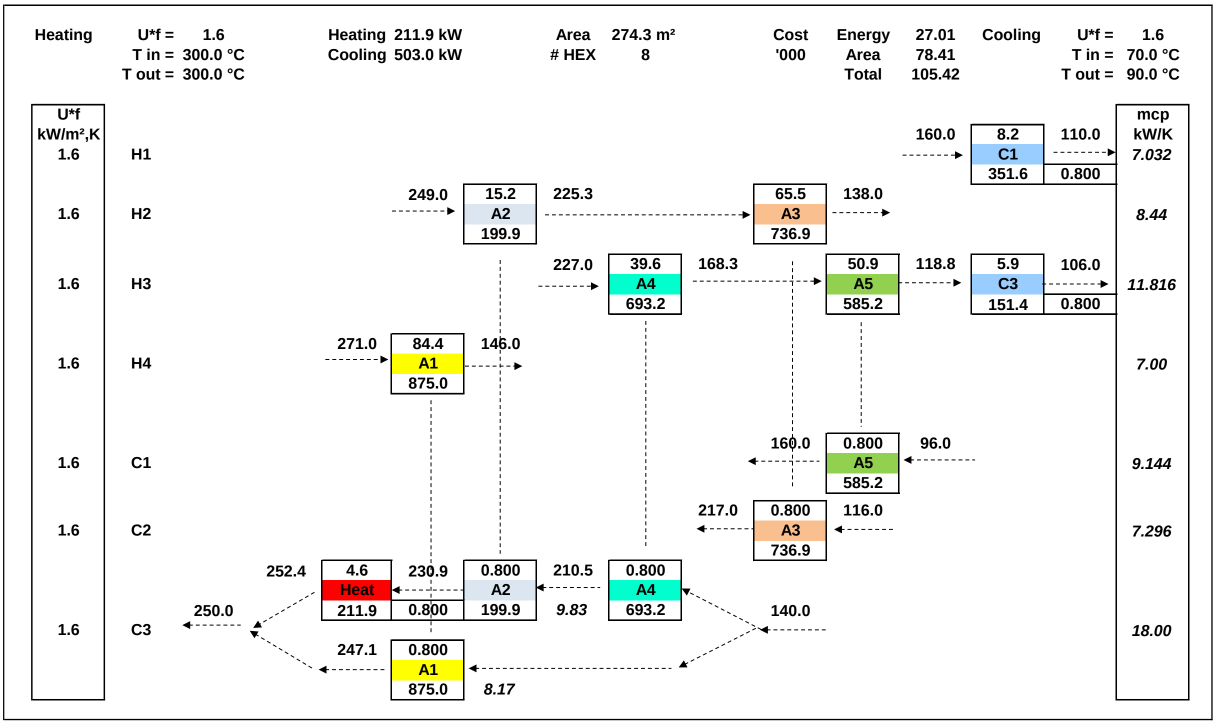


Figure 7.9

8 The 9SP Aromatics Plant from Linnhoff and Ahmad

The 9SP Aromatics Plant problem was first presented by Linnhoff and Ahmad in 1990 [53]. It was the first application of the pinch analysis methodology developed by Linnhoff and its success led to world-wide dissemination. Further studies have been published by Zhu et al. [54], Lewin [55], [114], Gcaba [56], Briones and Kokossis [48], Chakraborty and Ghosh [57], Pattekar [58], Liporace et al. [59], Pettersson [60], Bergamini et al. [61], Yerramsetty and Murty [62], Dipama et al. [63], Avila-Díaz et al. [64], Luo et al. [65], Toffolo [66], Laukkanen and Fogelholm [67], Bogataj and Kravanja [68], Azeez et al. [69], Usman [70], Hussein et al. [71], Huo et al. [72], [96], Ghiasvand et al. [73], Peng and Cui [74], Núñez-Serna and Zamora [75], Pavão et al. [21], [76], [77], [78], , Chen et al. [79], Xiao et al. [80], Xu et al. [82], Rathjens and Fieg [83] and Caballero et al.[10]. It has also been studied by this author for networks with splits [84] and for networks without splits [85].

The data are given in Table 8.1, together with shift contributions obtained by crisscross optimisation prior to design.

Table 8.1

Tsupply	Ttarget	Heat	DT-shift	U*f	Descript.	mcp
°C	°C	MW	K	kW/K,m²	-	kW/K
327	40	28700	0	0.50	H1	100
220	160	9600	1	0.40	H2	160
220	60	9600	12	0.14	H3	60
160	45	46000	4	0.30	H4	400
100	300	20000	4	0.35	C1	100
35	164	9030	0	0.70	C2	70
85	138	18550	2	0.50	C3	350
60	170	6600	12	0.14	C4	60
140	300	32000	0	0.60	C5	200
330	250	24000	0	0.50	Heating	
15	30	31720	0	0.50	Cooling	

Cost data

Heating : 60.0 $/kW,year   Cooling : 6.0 $/kW,year

HEX Cost : 2000 + 60 x Area $/year

Composite curves are shown in Figure 8.1; hot stream H4 is causing the pinch. The trade-off curve is shown in Figure 8.2 for a pinched system; there is a minimum for a heating load of 24075 kW. Details of the synthesis procedure have been explained in [85].

The original grid resulting from the analysis shows 15 integration bands which can be reduced to a minimum of 5 (Table 8.2). Using the grid diagram of Table 8.2, an initial network can be generated by LP targeting minimum surface area. That network can be optimised for less units and minimum cost, leading to a number of optimum solutions. Starting with a higher number of bands can sometimes lead to better solutions. An overview of the best solutions for networks with splits is shown in Table 8.3 for networks with 18 units down to 10. As can be seen in Table 8.3, the cost of the best networks is very close to the results of the analysis; the difference is marginal. These networks from Table 8.3 are shown in the Figures 8.3 through 8.11.

A study had also been done on networks without splits [86]. The results, updated with the latest research, are also shown in Table 8.3. These networks are shown in Figures 8.12 through 8.19.

An extensive list of the results in published networks can be found in Table 8.4. The network published by Pettersson [60] with a cost of 2904.95 k$/year was developed with isothermal splits. The cost can be reduced by incremental evolution to 2896.77 k$/year and further down to 2892.93 k$/year when using non-isothermal splits. This was confirmed by Rathjens and Fieg in [83], using complex mathematical tools, however. The study of Avila-Diaz [64] reports a network with a cost of 2904.39 k$/year. Incremental evolution combined with non-isothermal splits would bring the cost of that network down to 2892.42 k$/year. Many published networks had to be corrected after detailed reviews. For studies that reported more solutions, only the best network was withheld.

During the search, 12 networks were developed with a cost below 2892.42 k$/year, being the cost of the best network published by Avila-Diaz after further optimisation. More than 50 networks were developed with a cost below 2900 k$/year whilst all published networks have a cost above that threshold.

Table 8.2

Process 9SP Aromatcs												
		area (m²	**#HEX**	**AreaCost**								
	Heatit	**17486**	**15**	**1254.05**								
	Designi	**17650**	**23**	**1281.47**								
Stream	**Tsupply**	**Ttarget**	**Heat**	**Shift**	**U*f**	**mcp**						
-	**°C**	**°C**	**kW**	**K**	**kW/m²,K**	**kW/K**			**Bands**			
							1	**2**	**3**	**4**	**5**	
Heating	**330**	**250**	**24075**	**0**	**0.50**	**300.9**	**330.0**	**250.0**				
H1	**327**	**40**	**28700**	**0**	**0.50**	**100.0**	**327.0**	**219.0**	**161.5**	**121.0**	**98.3**	**40.0**
H2	**220**	**160**	**9600**	**1**	**0.40**	**160.0**		**220.0**	**160.0**			
H3	**220**	**60**	**9600**	**12**	**0.14**	**60.0**		**220.0**	**180.3**	**133.0**	**110.3**	**60.0**
H4	**160**	**45**	**46000**	**4**	**0.30**	**400.0**			**160.0**	**125.0**	**102.3**	**45.0**
C1	**100**	**300**	**20000**	**4**	**0.35**	**100.0**	**300.0**	**181.1**	**136.0**	**100.0**		
C2	**35**	**164**	**9030**	**0**	**0.70**	**70.0**		**164.0**	**140.0**	**104.0**	**35.0**	
C3	**85**	**138**	**18550**	**2**	**0.50**	**350.0**			**138.0**	**102.0**	**85.0**	
C4	**60**	**170**	**6600**	**12**	**0.14**	**60.0**		**170.0**	**128.0**	**92.0**	**60.0**	
C5	**140**	**300**	**32000**	**0**	**0.60**	**200.0**	**300.0**	**185.1**	**140.0**			
Cooling	**15**	**30**	**31795**	**0**	**0.50**	**2119.67**					**30.0**	**15.0**

Table 8.3	Heating	Area	# units	# splits	Energy	Capital	Total	EMAT
	MW	m²	-	-	'000/y	'000/y	'000/y	K
Analysis	24.075	17486	15	-	1635.27	1254.05	2889.32	-
LP-network	24.075	17292	23	-	1635.27	1281.47	2916.74	10.6
Design	24.270	17233	18	9	1648.15	1242.30	2890.44	16.5
Networks with splits	24.280	17234	17	8	1648.80	1240.38	2889.18	16.6
	24.328	17202	16	7	1651.97	1236.14	2888.11	16.6
	24.365	17250	15	5	1654.38	1237.47	2891.85	14.2
	23.930	17702	14	2	1625.70	1267.12	2892.82	14.1
	24.093	17571	13	2	1636.46	1255.95	2892.41	13.8
	24.159	17642	12	3	1640.81	1258.90	2899.72	14.7
	24.126	17843	11	1	1638.60	1271.03	2909.64	8.8
	25.721	16919	10	1	1743.91	1204.35	2948.26	10.4
Design	24.46	17218	16	0	1660.55	1237.17	2897.72	12.2
Networks without splits	24.02	17628	15	0	1631.84	1263.93	2895.77	11.9
	24.21	17483	14	0	1643.85	1251.78	2895.63	11.5
	24.17	17644	13	0	1641.74	1261.08	2902.82	12.4
	24.30	17703	12	0	1650.25	1263.22	2913.47	8.6
	26.15	16160	11	0	1772.29	1153.19	2925.47	11.8
	25.75	16904	10	0	1745.49	1203.27	2948.76	10.8

Table 8.4

	Heating	Area	# units	# splits	Energy	Capital	Total	EMAT
Published networks	MW	m²	-	-	'000/y	'000/y	'000/y	K
Linnhoff & Ahmad (1990)	25.310	17270	13	0	1716.78	1234.89	2951.67	10.1
Zhu et al. (1995)	26.830	15475	10	0	1817.10	1103.34	2920.34	7.3
Gcaba (1998) °)	37.185	10420	11	0	2500.53	751.42	3251.95	4.7
Lewin (1998)	25.690	16875	11	0	1741.86	1203.26	2945.12	10.0
Pattekar (1999) °)	26.357	17740	14	0	1785.87	1269.80	3055.67	7.9
Briones et al. (1999)	25.364	17483	11	0	1720.34	1245.79	2966.14	6.7
Chakraborty at al. (1999)	25.684	17202	10	0	1741.46	1224.11	2965.50	9.9
Liporace et al. (2001)	25.620	17189	11	1	1737.24	1225.24	2962.48	16.1
Pettersson (2005)	24.266	17473	17	7	1647.88	1257.08	2904.95	14.1
Pettersson optimised	*24.154*	*17406*	*17*	*7*	*1640.48*	*1252.44*	*2892.93*	*16.0*
Bergamini et al. (2007)	23.600	18588	15	0	1603.92	1331.18	2935.10	12.4
Dipama et al. (2008)	27.810	16440	16	0	1881.78	1182.84	3064.62	26.0
Avila-Diaz et al. (2008) °)	23.773	18019	13	2	1615.34	1287.36	2902.70	9.9
Avila-Diaz optimised	*24.076*	*17587*	*13*	*2*	*1635.34*	*1257.09*	*2892.42*	*13.9*
Yerramsetty et al. (2008)	25.883	16791	15	0	1754.58	1205.40	2959.98	12.0
Fieg et al. (2009)	23.615	18420	14	3	1604.88	1317.42	2922.30	11.3
Toffolo (2009)	23.678	18300	15	4	1609.07	1311.03	2920.10	13.3
Gupta and Ghosh (2010)	20.376	24388	12	0	1391.14	1731.13	3122.27	7.4
Azeez (2012) °)	23.903	17989	17	6	1623.90	1293.25	2917.15	16.9
Bogataj & Kravanja (2012	23.630	18816	14	0	1605.90	1345.14	2951.04	10.4
Huo revised (2012)	24.220	17773	13	2	1644.84	1270.12	2914.96	12.0
Hussein et al. (2013) revis	23.080	21071	15	0	1569.60	1504.95	3074.55	17.8
Usman et al. (2013) °)	22.400	20423	11	0	1451.62	1524.72	2976.34	16.2
Ghiasvand et al. (2014) °)	25.010	17182	16	0	1696.98	1234.76	2931.74	10.8
Peng and Cui (2015)	24.495	17745	15	0	1662.99	1272.12	2935.11	15.2
Núñez-Serna et al. (2016)	23.411	18695	15	0	1591.47	1338.64	2930.11	11.8
Pavão et al. (2018)	24.758	17166	14	2	1680.34	1229.59	2909.93	11.2
Rathjens and Fieg (2019)	24.237	17698	12	4	1645.93	1262.84	2908.77	12.4
Caballero et al. (2021)	23.865	17709	15	5	1621.43	1283.22	2904.65	15.1

°) revised

Figure 8.1

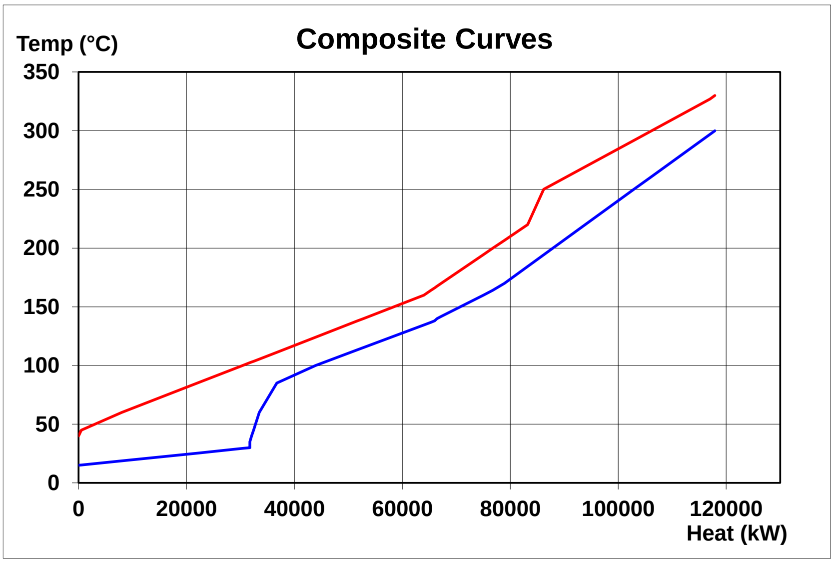
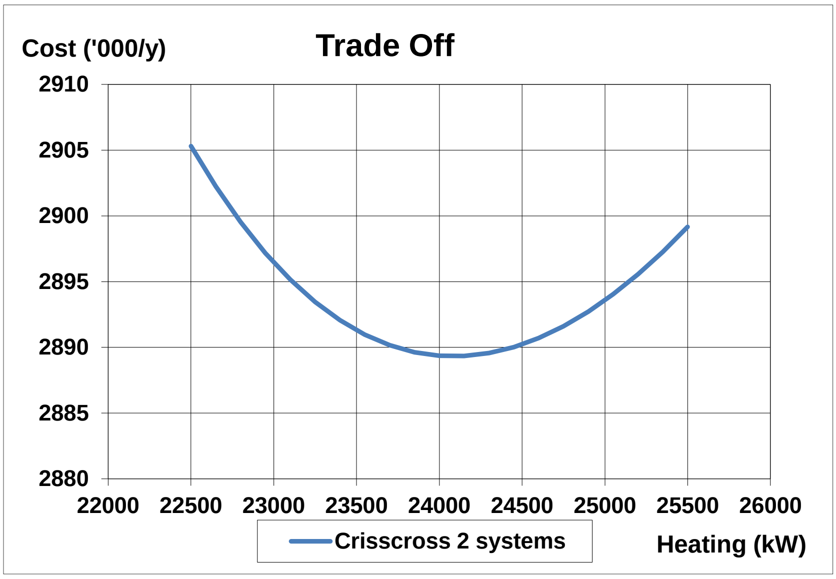
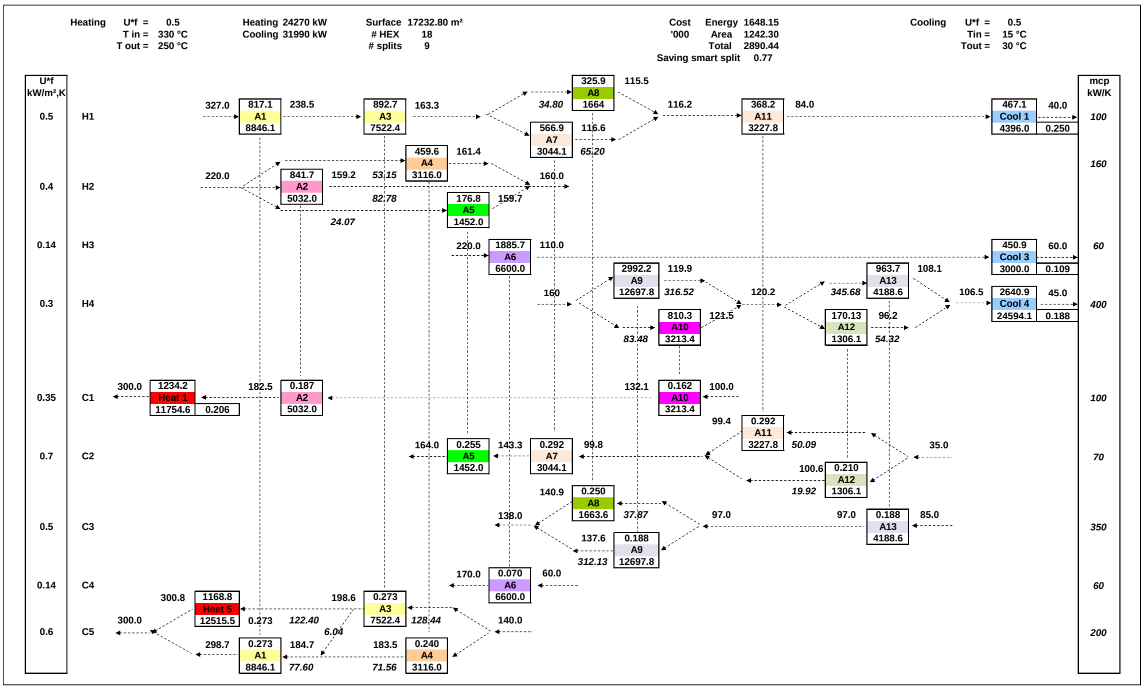


Figure 8.2





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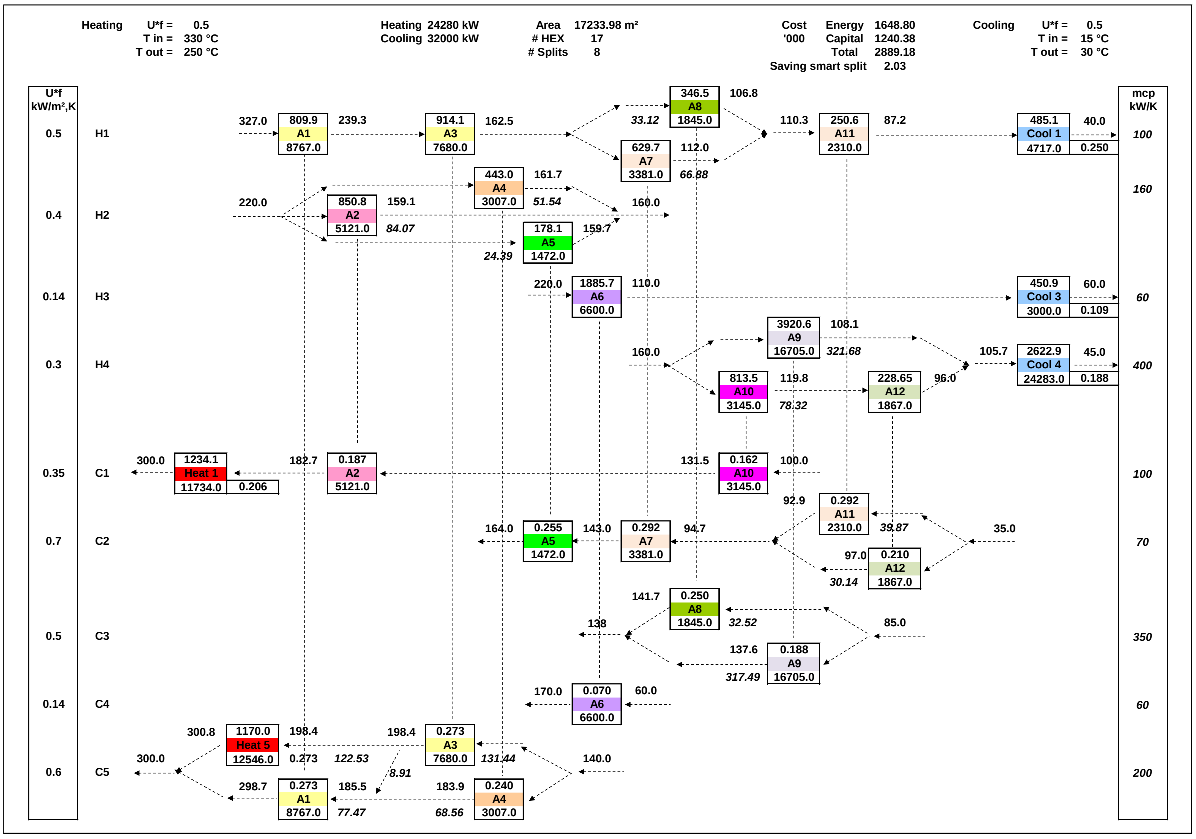

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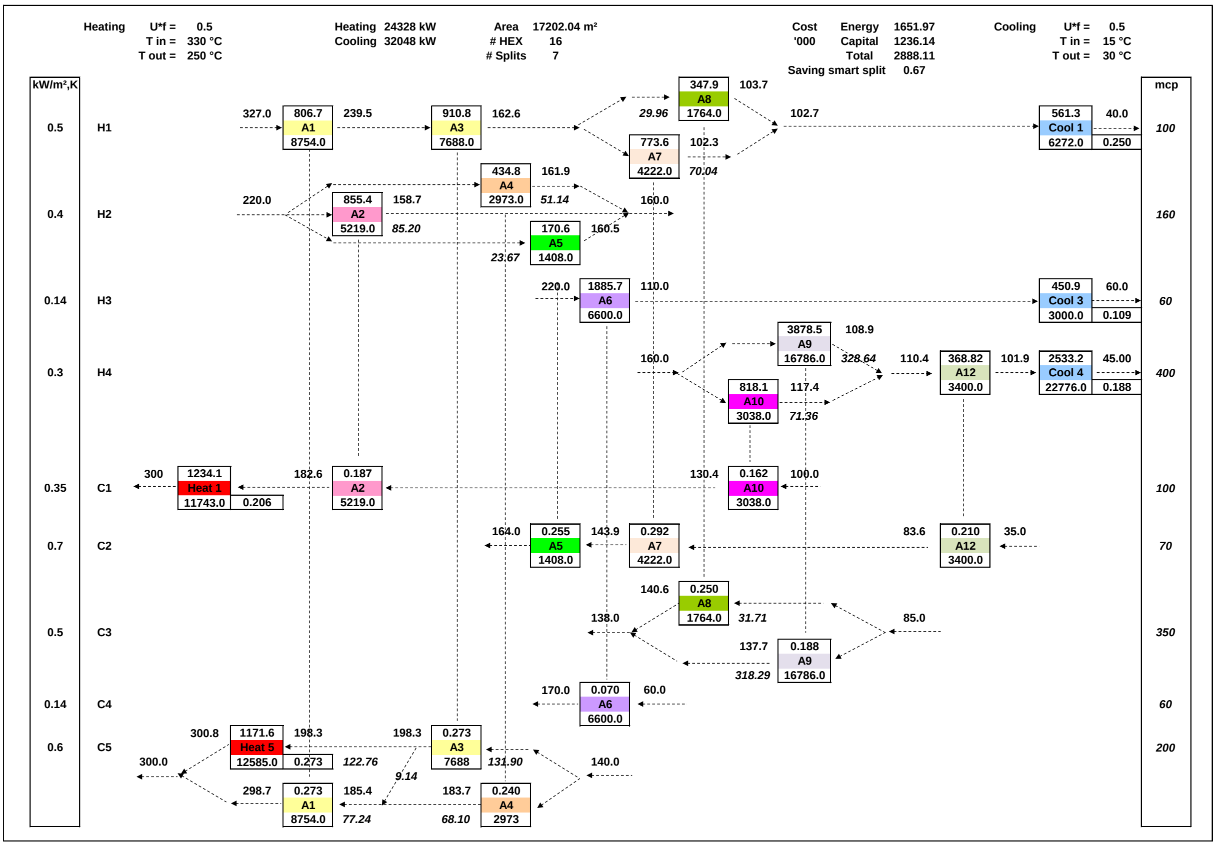

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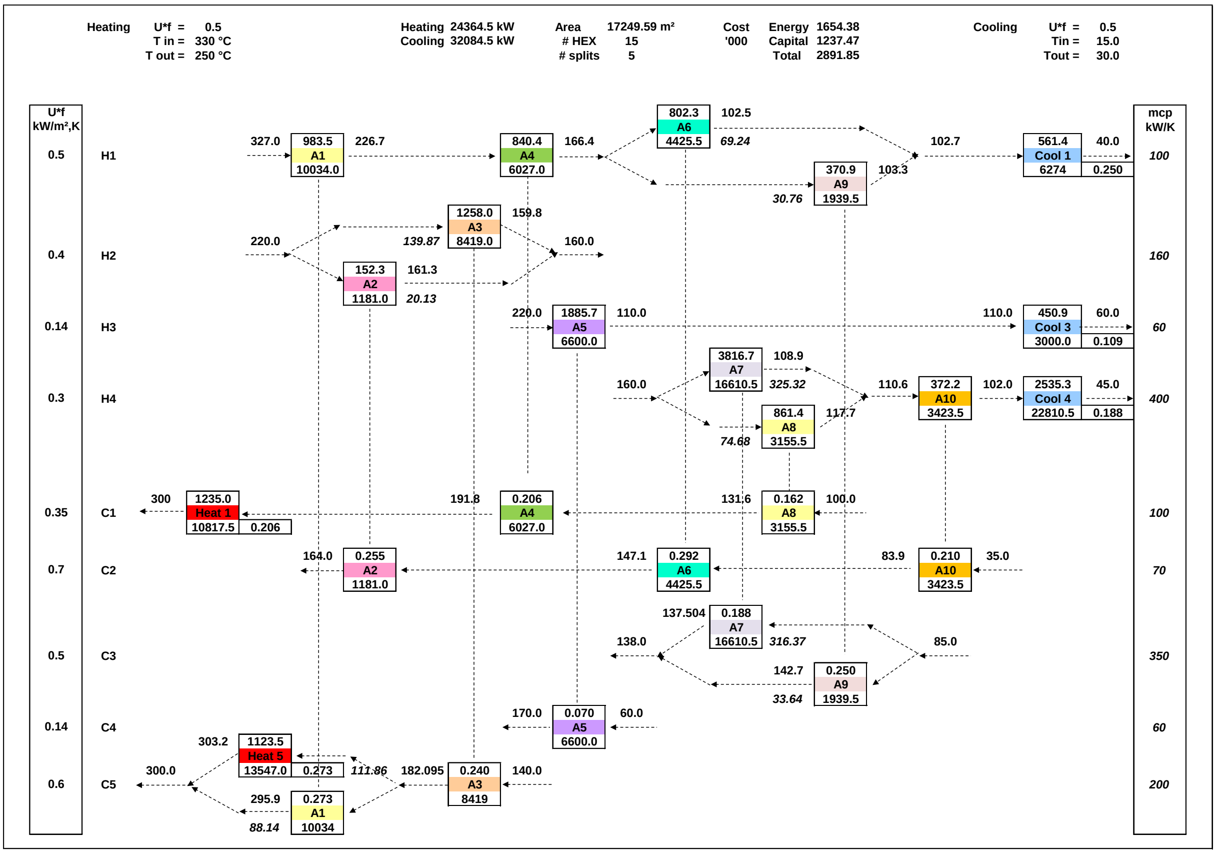

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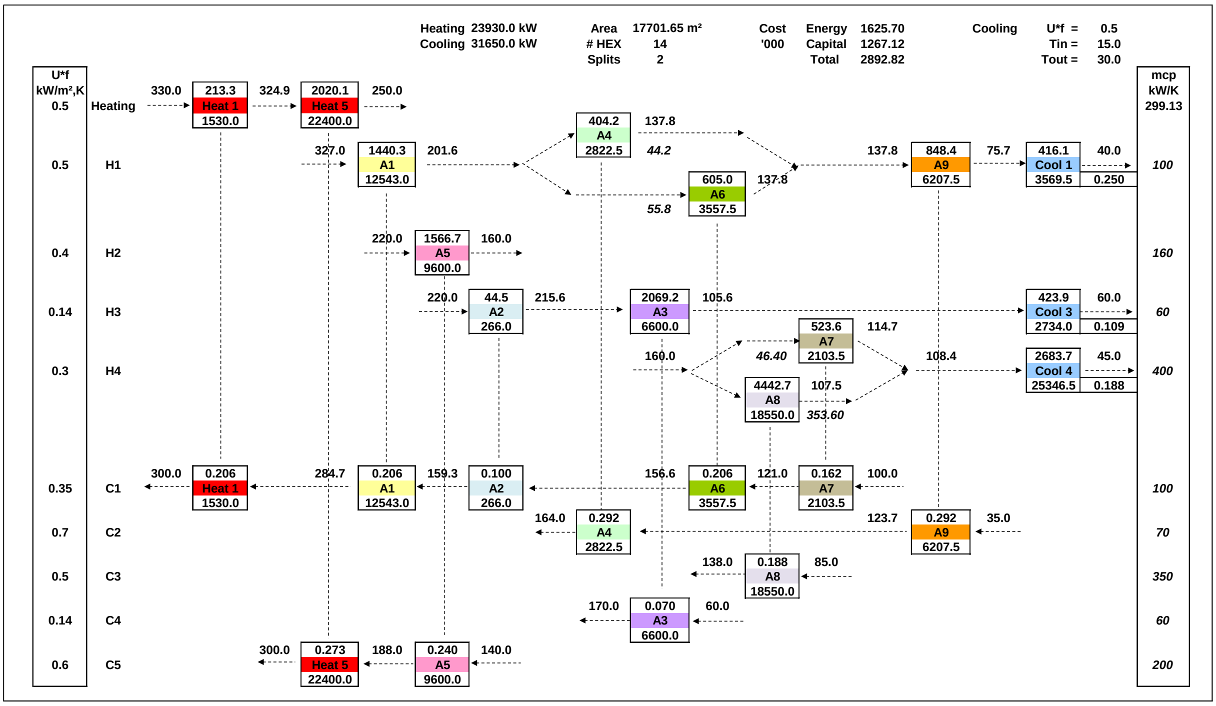

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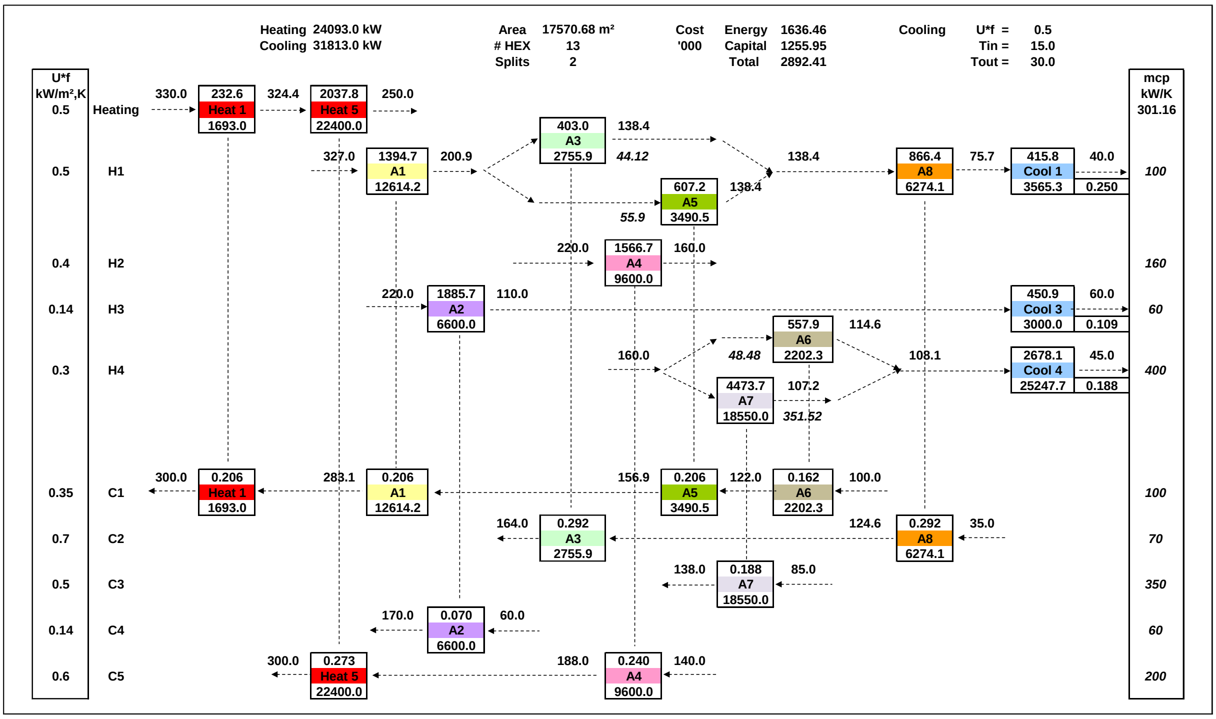

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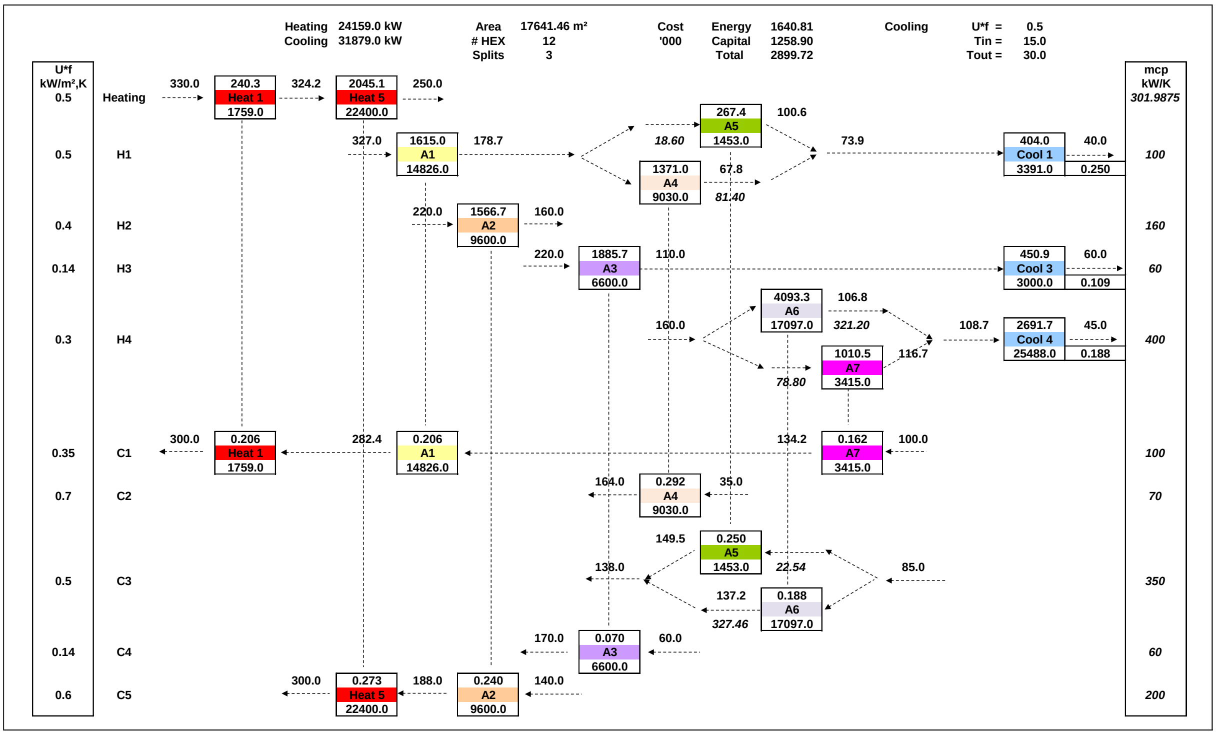

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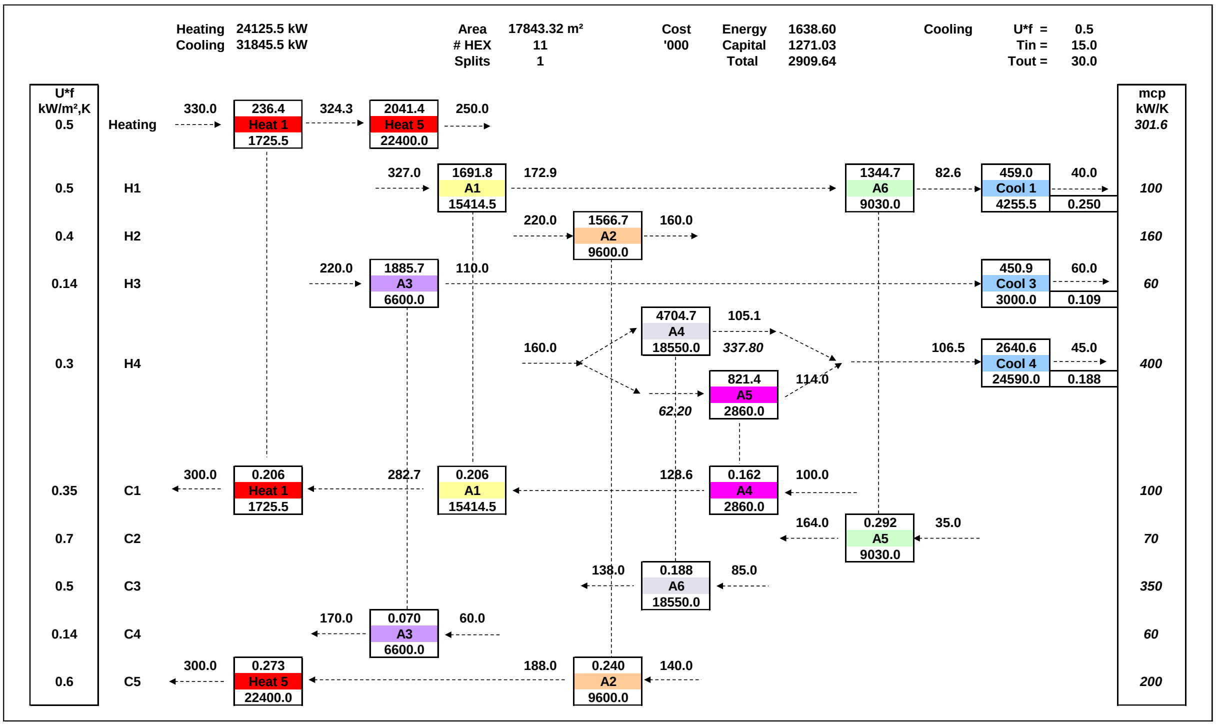

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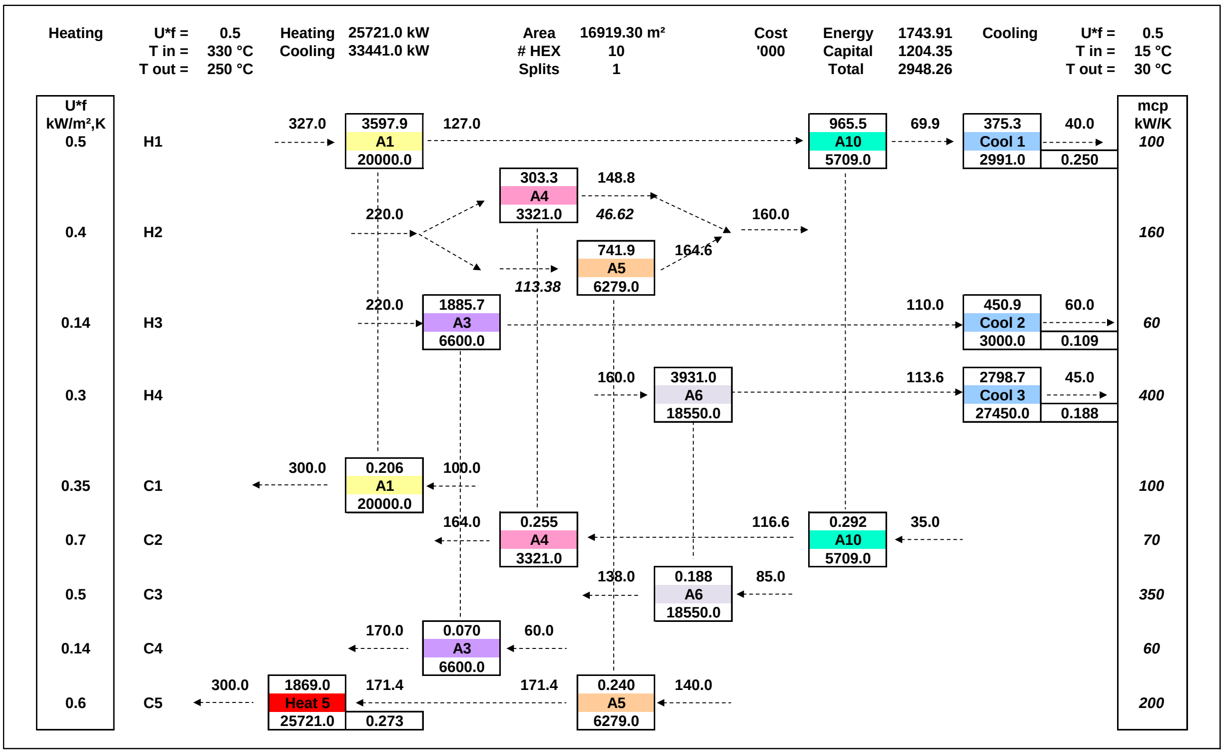

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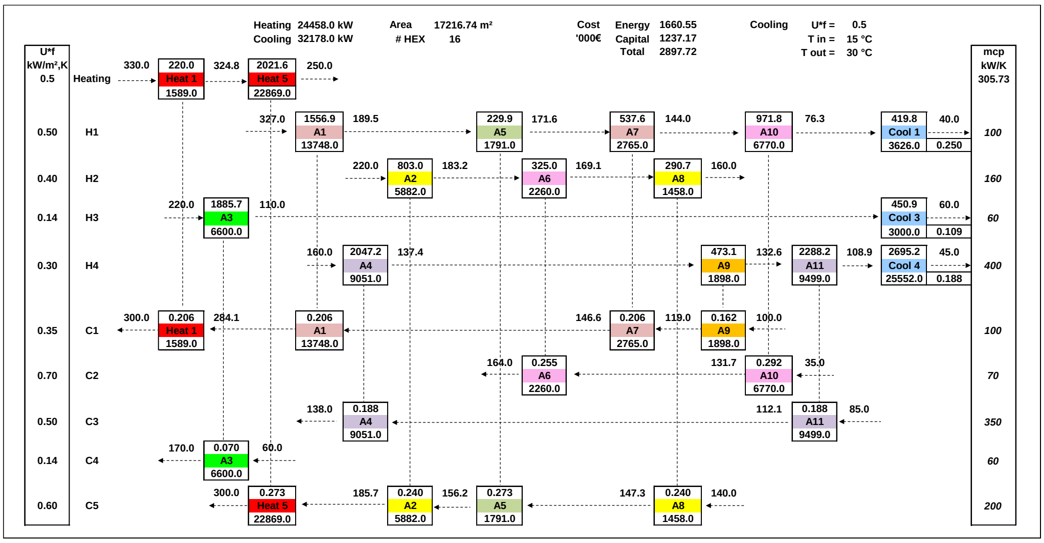

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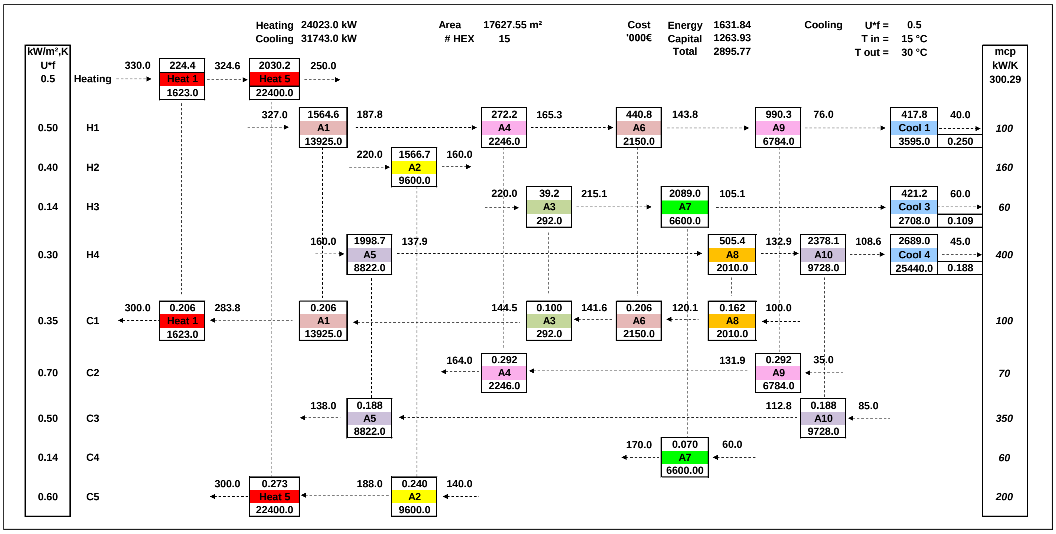

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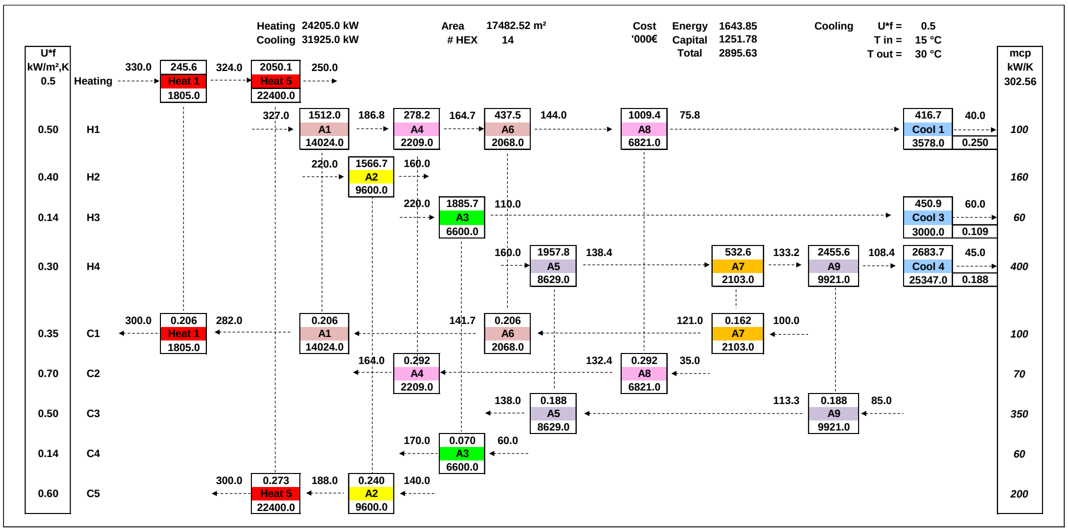

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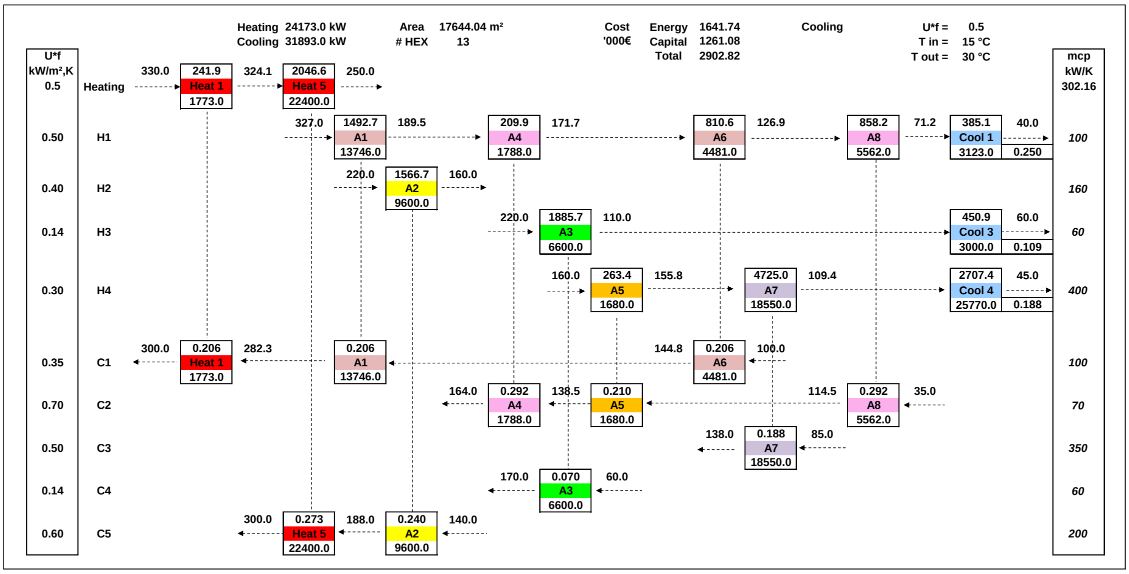

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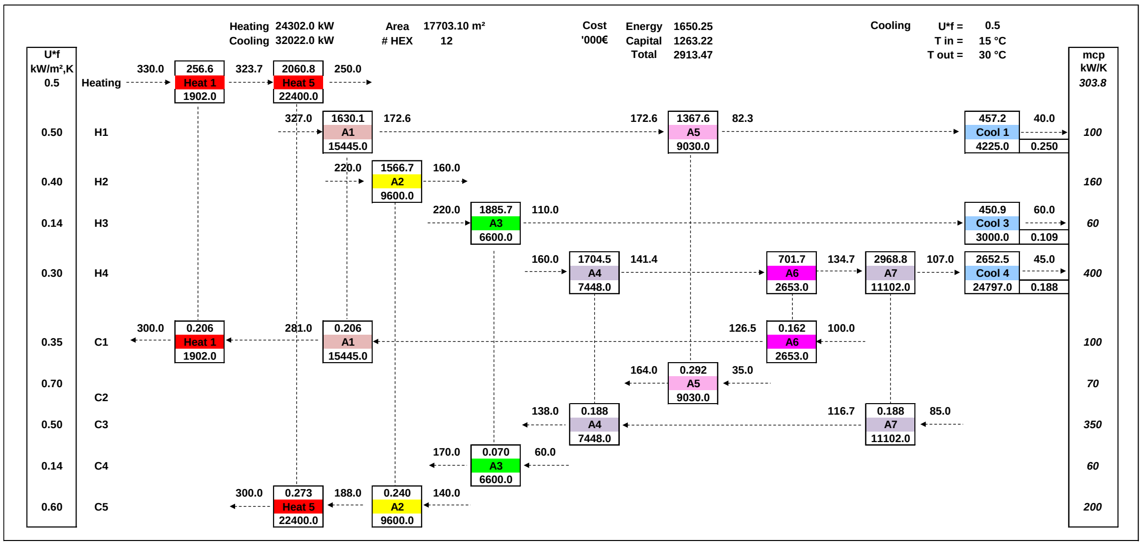

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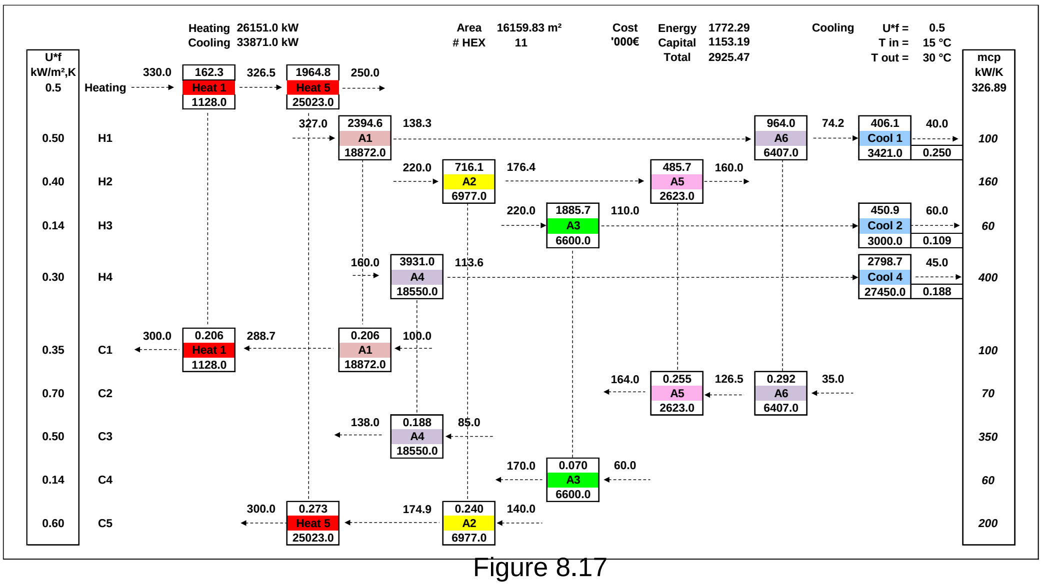

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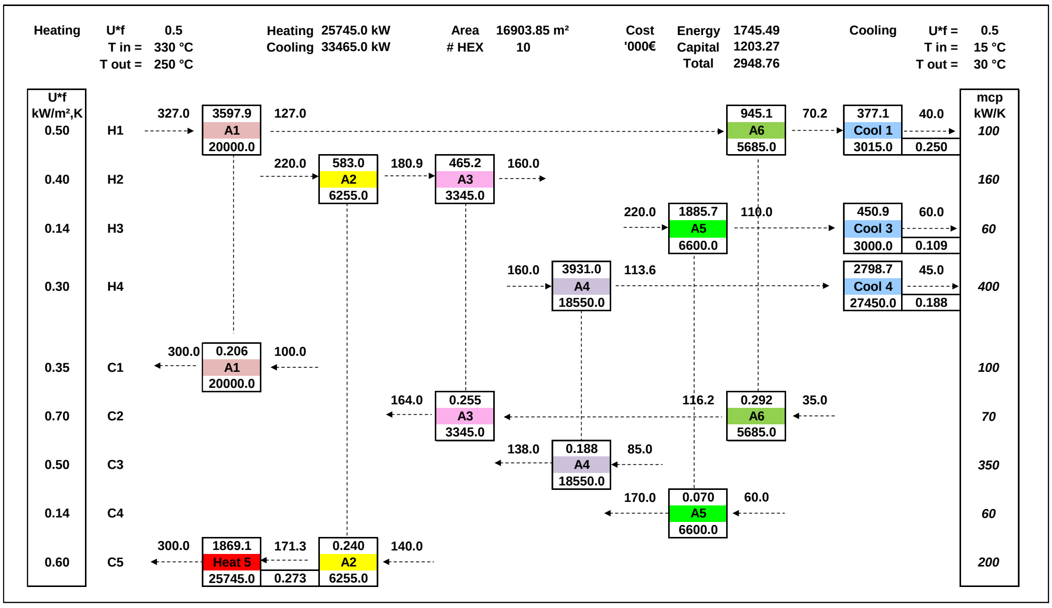


Figure 8.18

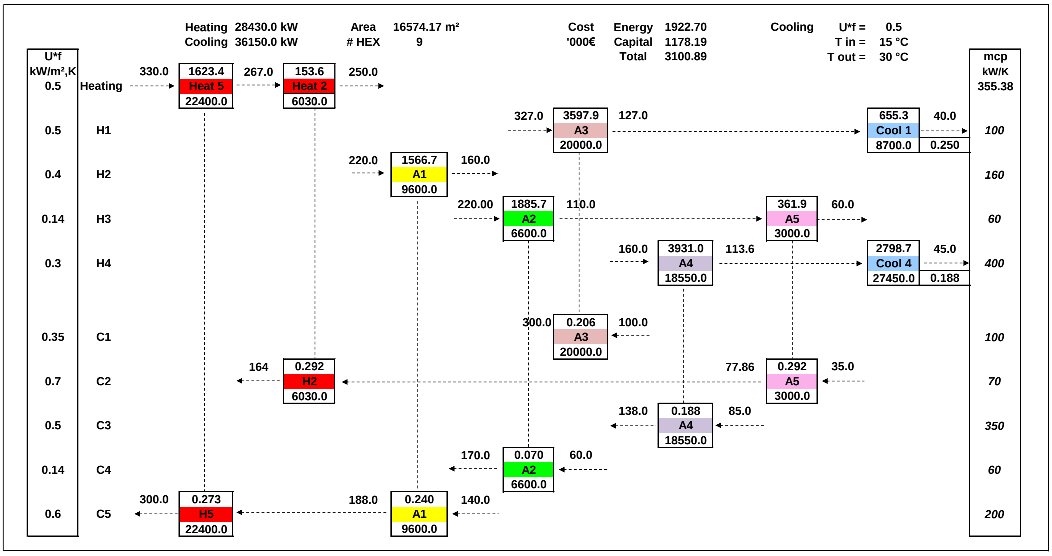


Figure 8.19

9 The 10 streams problem from Ahmad (6H4C)

This 10 streams example was first presented by Ahmad in 1985 [12]. It was also studied by Ravagnani et al. [88], [95], Yerramsetty & Murty [89], Khorasany & Fesanghary [90], Bao et al. [92], Gorji-Bandpy et al. [94], Huo et al. [966], Laukkanen et al. [67], He & Cui [91], Peng & Cui [74], Myankooh & Shafiei [93], Dina et al. [81, Zhang et al. [114], Huang et al. [86], Huang & Karimi [87], Chen et al. [79], Pavão et al. [77], Rathjens & Fieg [83], Caballero et al. [10] and Xu et al. [34]. It comprises 6 hot streams and 4 cold streams, 1 hot utility and 1 cold utility. The data set is shown in Table 9.1.

Table 9.1

Tsupply	Ttarget	Heat	U*f	mcp	Descript.
°C	°C	kW	kW/K,m²	kW/K	-
85	45	6252	0.05	156.3	H1
120	40	4000	0.05	50.0	H2
125	35	2151	0.05	23.9	H3
56	46	12500	0.05	1250.0	H4
90	86	6000	0.05	1500.0	H5
225	75	7500	0.05	50.0	H6
40	55	7000	0.05	466.667	C1
55	65	6000	0.05	600.0	C2
65	165	18000	0.05	180.0	C3
10	170	13008	0.05	81.3	C4
200	198		0.05		Heating
15	20		0.05		Cooling

Cost data

Heating : 100.0 $/kW,year Cooling : 15.0 $/kW,year

HEX cost : 8000 + 60 x Area (m²) $/year

It is appropriate to mention the important differences between the original data used by Ahmad and those in later studies: in the latter, hot stream H5 can be combined with cold stream C2, creating an independent system, in the former hot stream H5 has a load of 7500 kW which excludes such system. In the former, cold stream C3 has a load of 19500 kW, in the latter that load is only 18000 kW; in the former, utility temperatures should be estimated and best estimates differ from the data used in the latter. Consequently, no valid comparison can be made between the results of the two data sets. Most of the studies, however, have used the data as reported by Khorasany et al. [90] that also include fix costs and which are given in Table 9.1. In results of networks without fix costs, such costs have been added to make results comparable. In many studies, an approximate heat capacity flow rate of 466.7 kW/K was used for cold stream C1; this was adjusted to a value of 466.667 to generate a more precise heat load of 7000 kW for that stream.

Composite curves are shown in Figure 9.1. For an overall DeltaT of 16 K and lower, the pinch is caused by hot stream H4; for a DeltaT of 17 K and up to 32.3 K, the pinch is caused by cold stream C1; for a DeltaT above 32.5 K, the pinch is caused by hot stream H5. The trade-off in Figure 9.2 shows a minimum for a heating load of around 20300 kW; for that heating, the pinch would be caused by cold stream C1. Target costs for that heating are between 5690.5 and 5698.5 k$/year.

A series of networks was developed using a simplified grid, applying LP to obtain initial networks and further cost reduction by incremental evolution and stream swaps. Another series was developed using pinch design rules, combined with heuristics such as ticking of the biggest and/or smallest heat loads with one heat exchanger unit. This led to the networks with coolers on hot streams H1 and H4 and a single heat exchanger unit on hot stream H3.

A summary of the results is shown in Table 9.2, together with published results from literature. Networks with more than 20 units were not competitive because of too high fix cost and were not withheld. The optimum network has a cost of 5701.71 k$/year, which is within 0.2% of the target. For the best networks, using splits is advantageous as can be seen in Figure 9.3. The best networks with 19 units down to 9 are shown in Figures 9.4 through 9.14. During the search, 40 networks were developed within a cost range of 0.2% from the optimum.

Table 9.2

	Heating	Area	# HEX	# Splits	Energy	Capital	Total
Published networks	kW	m²	-	-	'000 $/y	'000 $/y	'000 $/y
Yerramsetty & Murty (2008) °°)	20745.4	56085	13	0	2301.65	3469.08	5770.73
Khorasany & Fesanghany (2009) °°)	19605.5	58100	12	0	2170.56	3582.00	5752.56
Laukkanen and Fogelholm (2011) °°)	20405.7	56367	14	2	2262.58	3494.00	5756.59
Gorji-Bandpy et al. (2011) °°)	19549.1	58196	15	0	2164.07	3611.70	5775.76
Huo et al. (2012) °°)	20007.5	57093	13	0	2216.79	3529.60	5746.39
He & Cui (2013) °°)	20267.4	56043	18	0	2246.67	3506.56	5753.23
Huang et al. (2014) °)	20207.0	56778	11	1	2239.73	3494.65	5734.39
Peng & Cui (2015) °°)	20038.0	56654	15	0	2220.29	3519.26	5739.56
Myankooh & Shafiei (2015) °°)	19992.3	57118	15	0	2215.04	3547.08	5762.11
Zhang et al. (2017) °)	20276.0	56001	19	0	2237.96	3512.06	5750.02
Bao (2018) °)	20323.7	56084	14	2	2253.15	3477.03	5730.19
Rathjens (2019) °)	20420.3	55883	12	2	2264.26	3448.97	5713.23
Caballero (2021) °)	20461.9	55616	13	3	2269.04	3440.97	5710.01
Xu et al. (2021) °)	20423.2	55597	13	2	2264.59	3439.84	5704.43
°) fine tuned or revised °°) revised with fix costs							
This research	20382	55395	19	2	2259.86	3475.7	5735.56
	20422	55325	18	3	2264.45	3463.53	5727.98
	20442	55311	17	2	2266.75	3454.64	5721.39
	20462	55331	16	2	2269.06	3447.83	5716.89
	20485	55324	15	2	2271.70	3439.44	5711.14
	20496	55378	14	2	2269.86	3434.67	5704.53
	20447	55506	13	2	2267.33	3434.38	5701.71
	20339	55972	12	2	2254.91	3454.33	5709.24
	20335	56299	11	2	2254.45	3465.96	5720.41
	20003	57431	10	1	2216.27	3525.86	5742.13
	20256	64077	9	0	2245.37	3916.60	6161.97

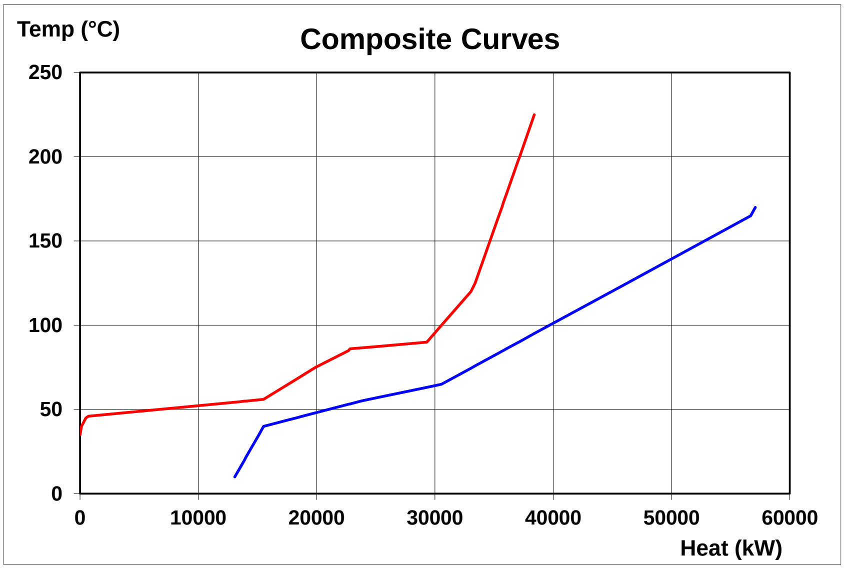


Figure 9.1

Figure 9.2

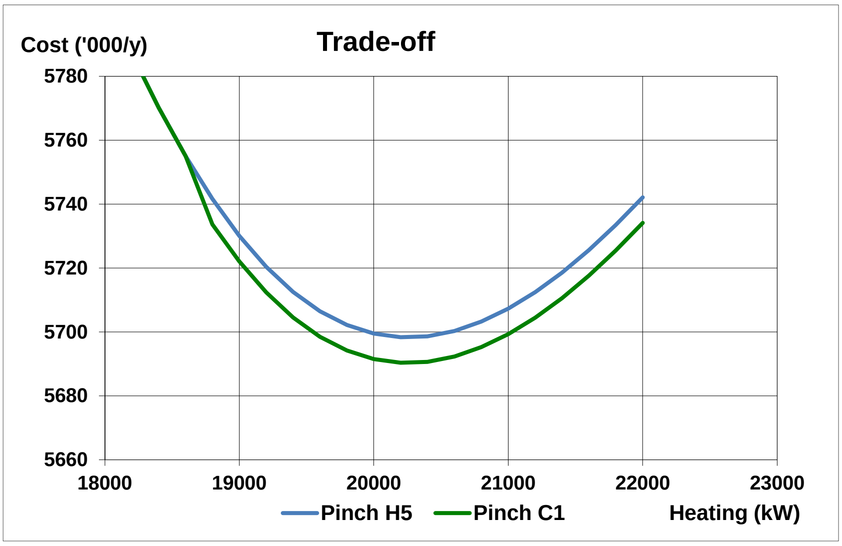
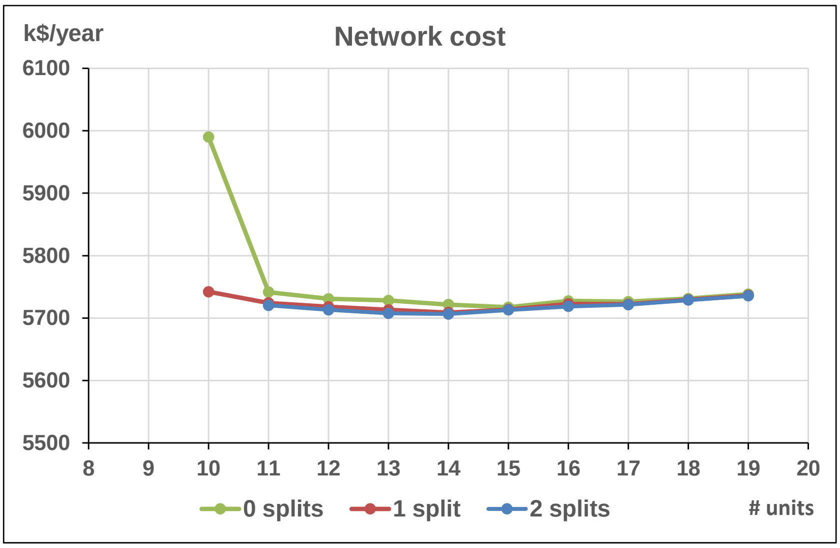
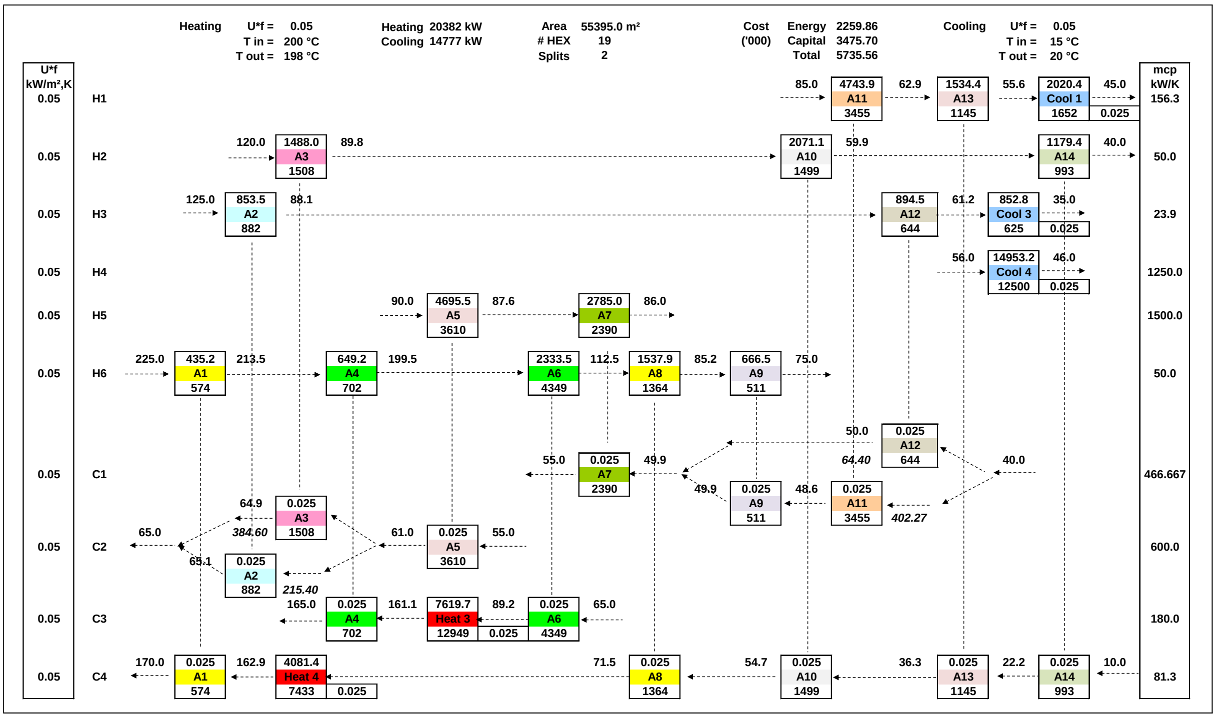


Figure 9.3





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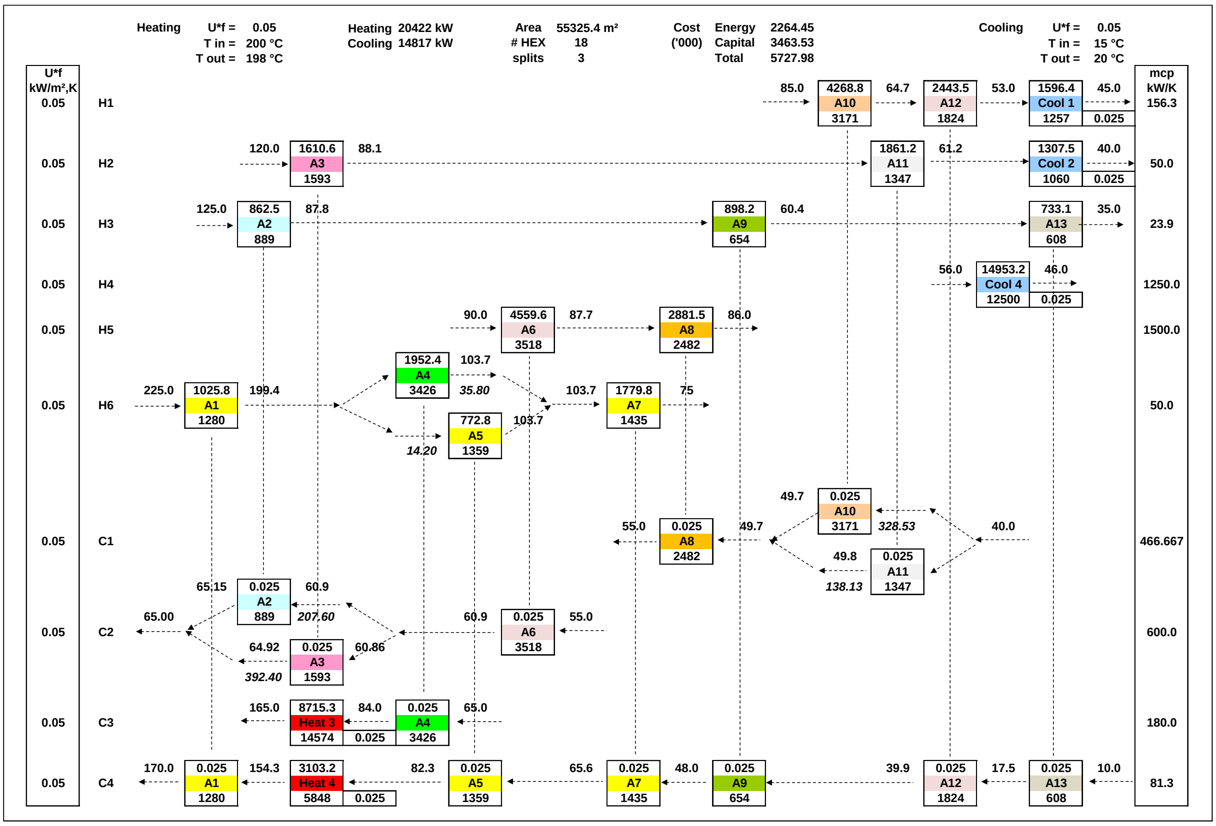

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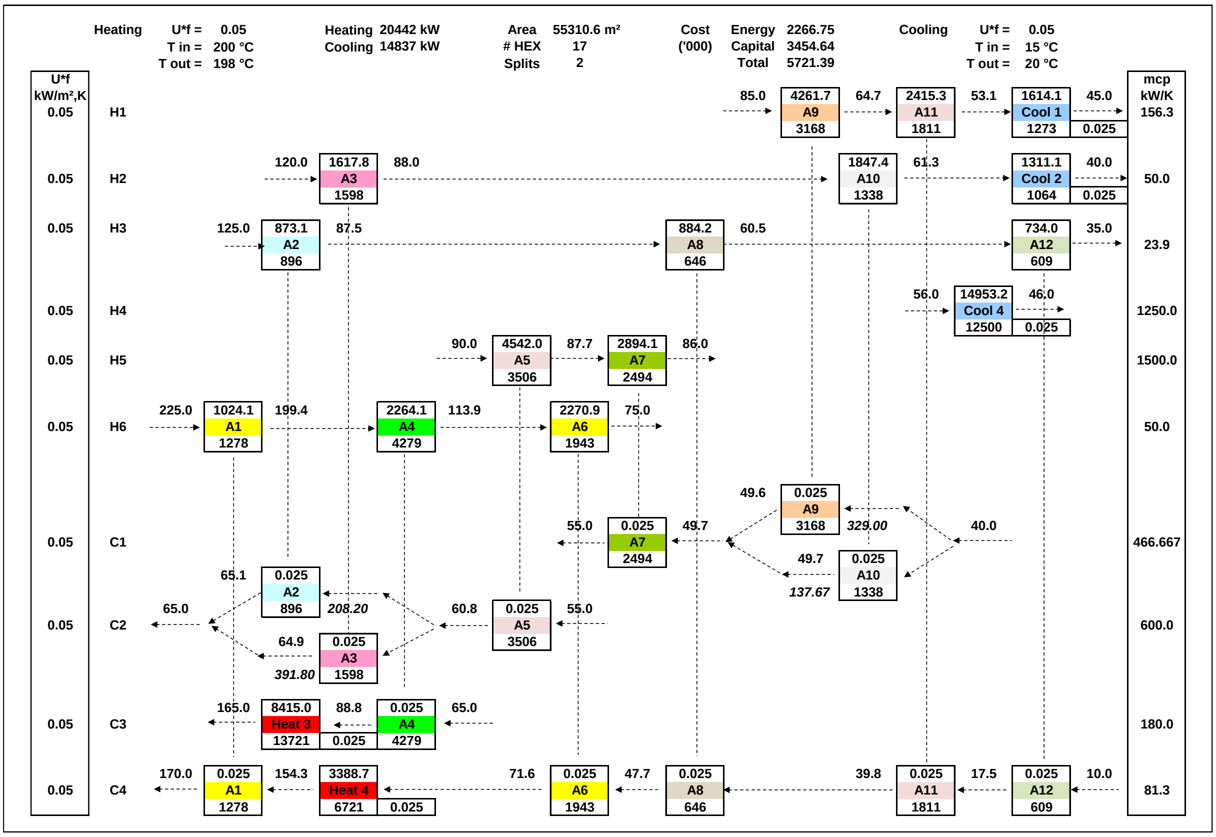

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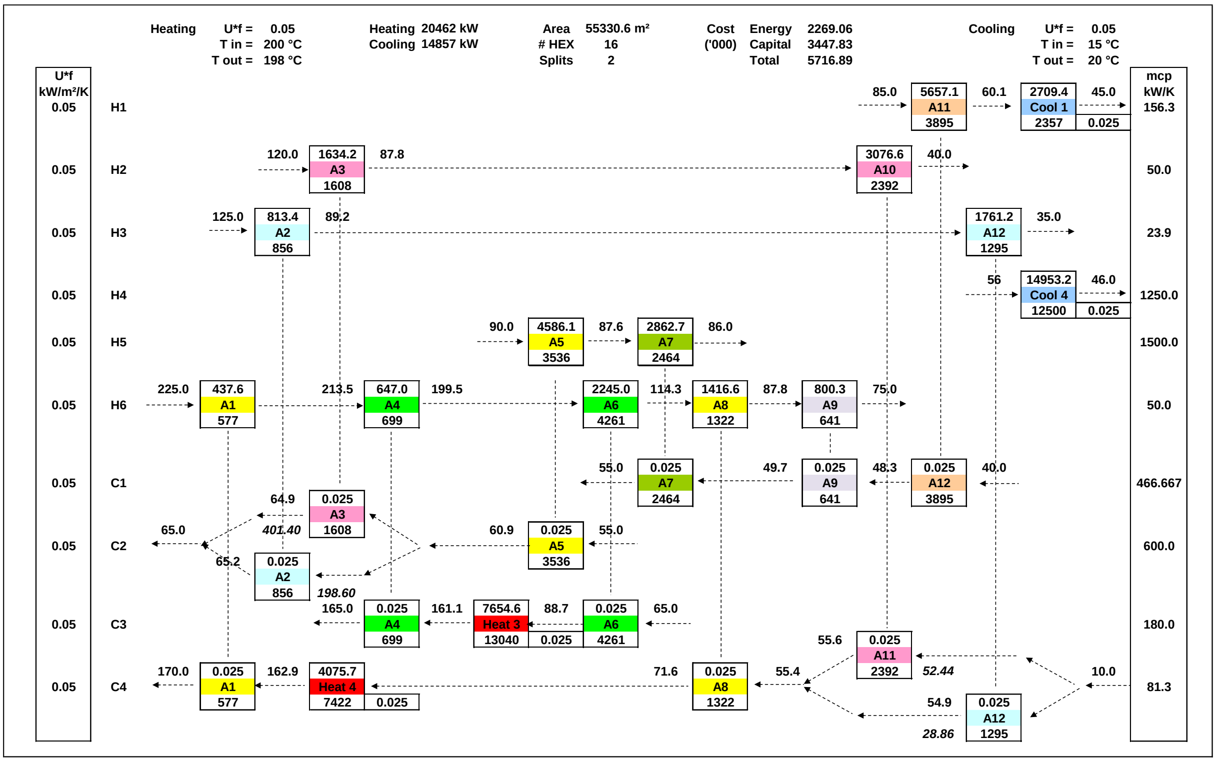

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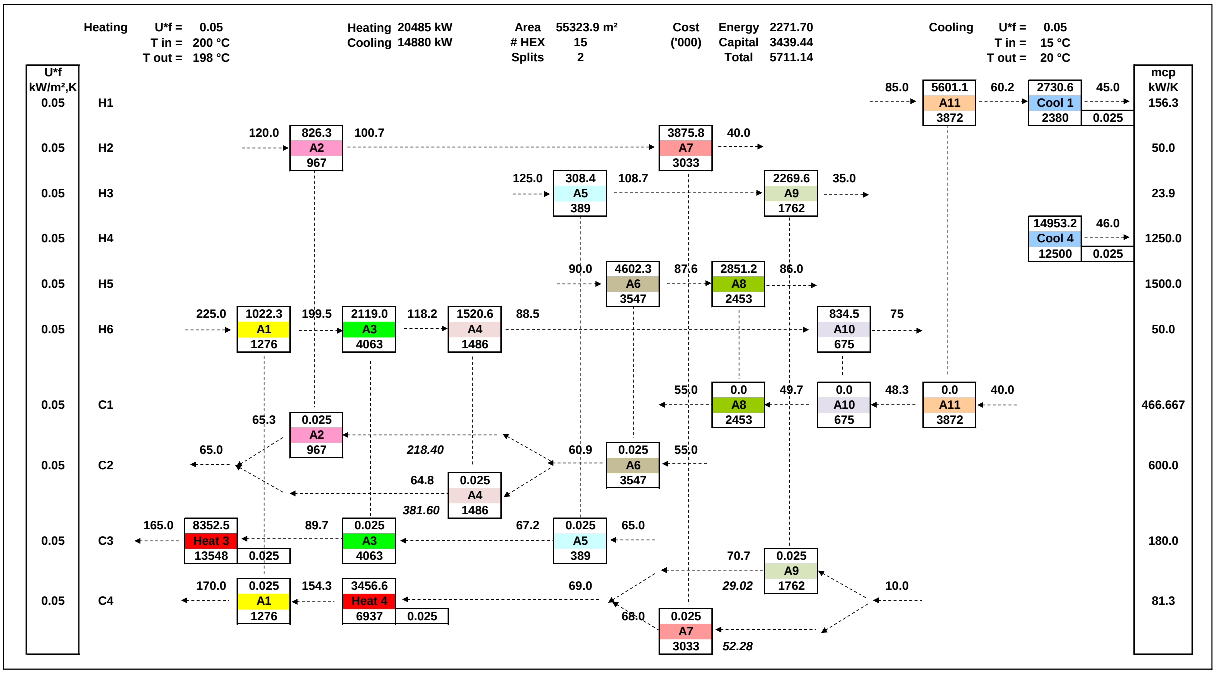

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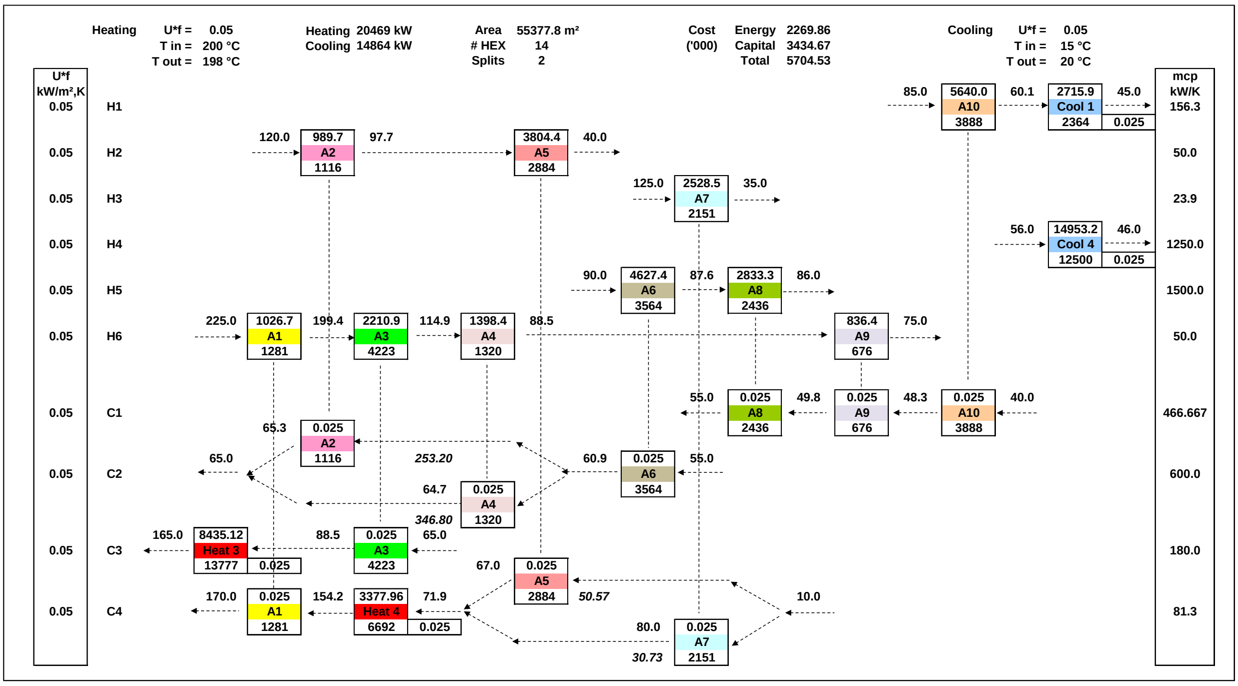

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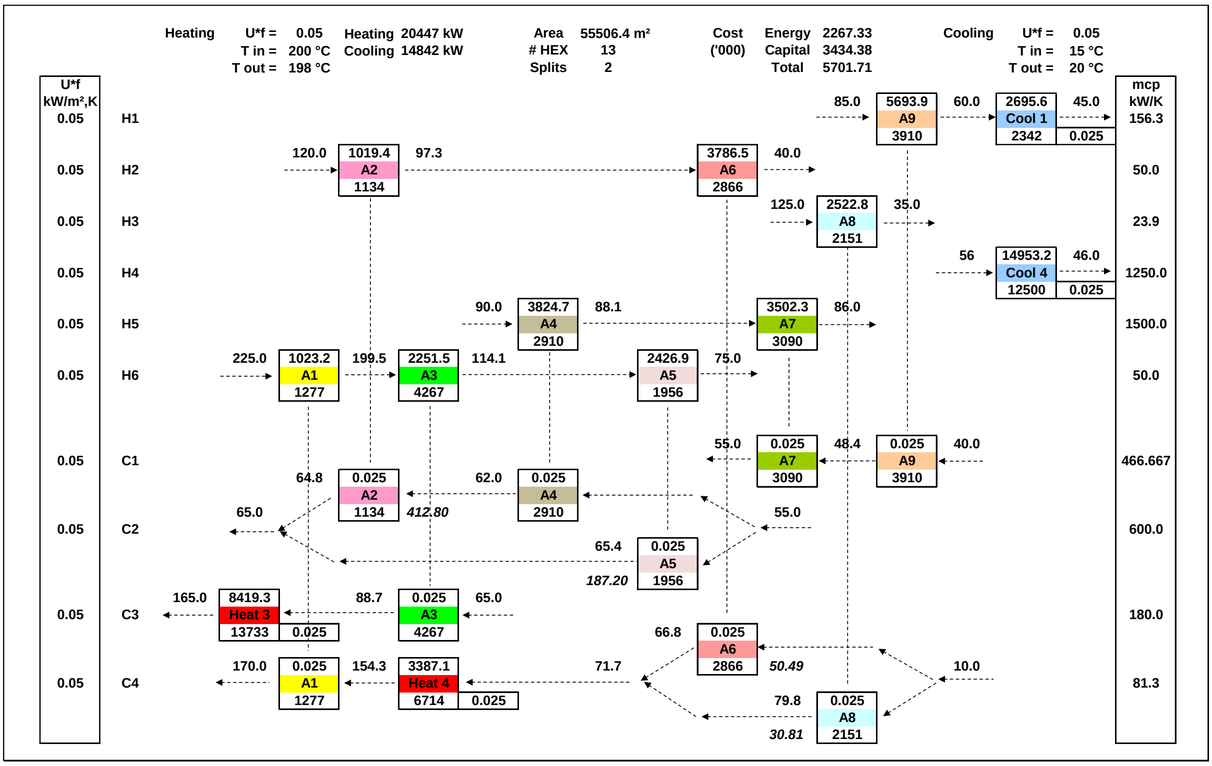

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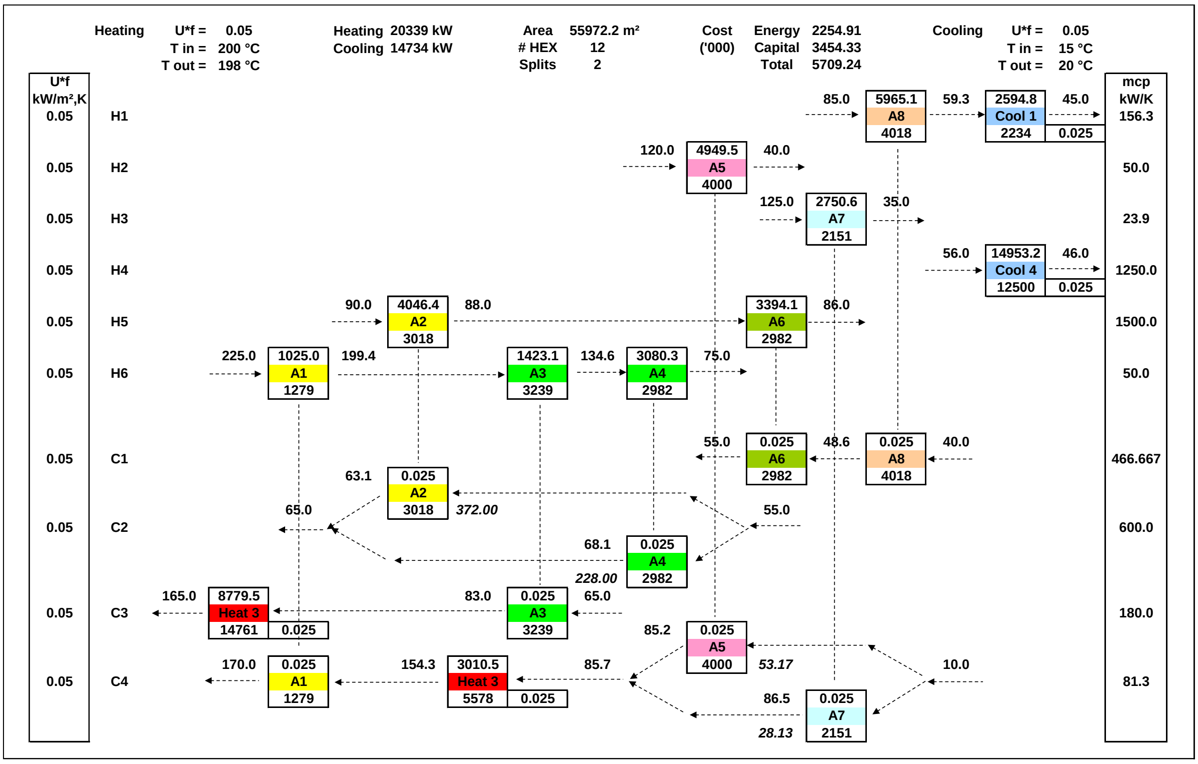
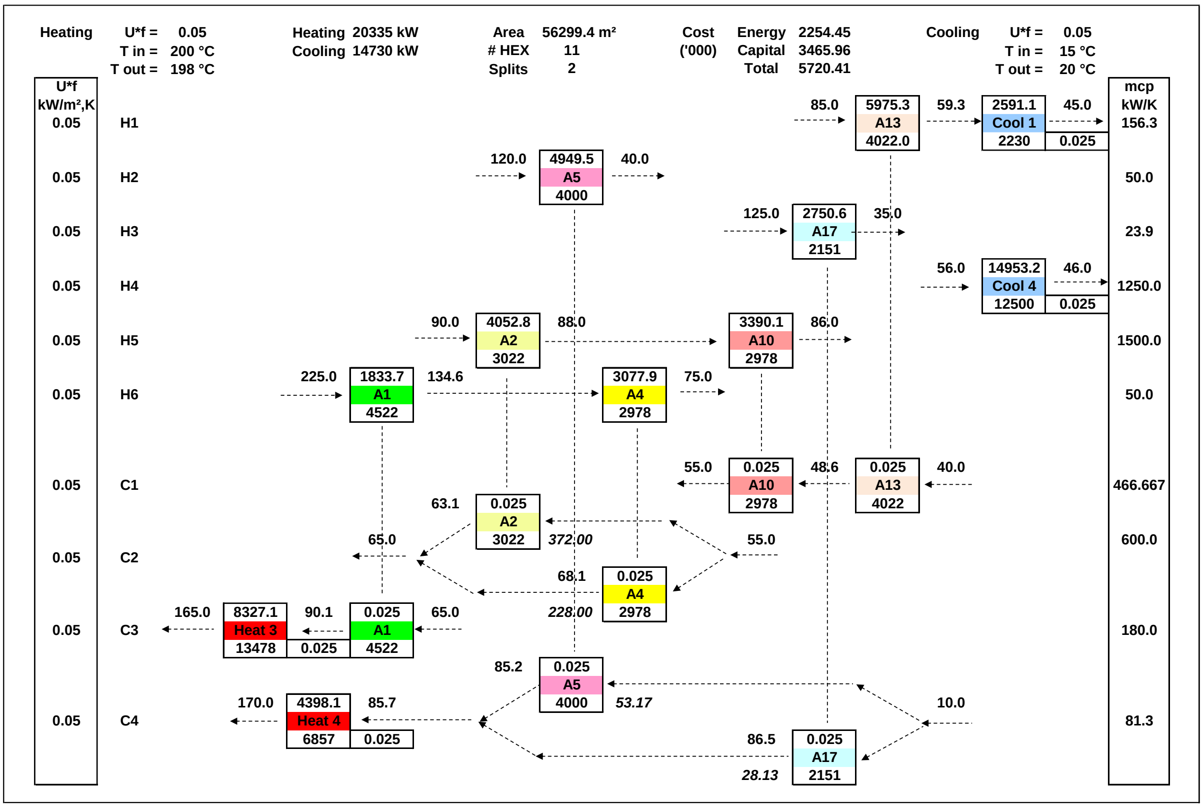


Figure 9.11



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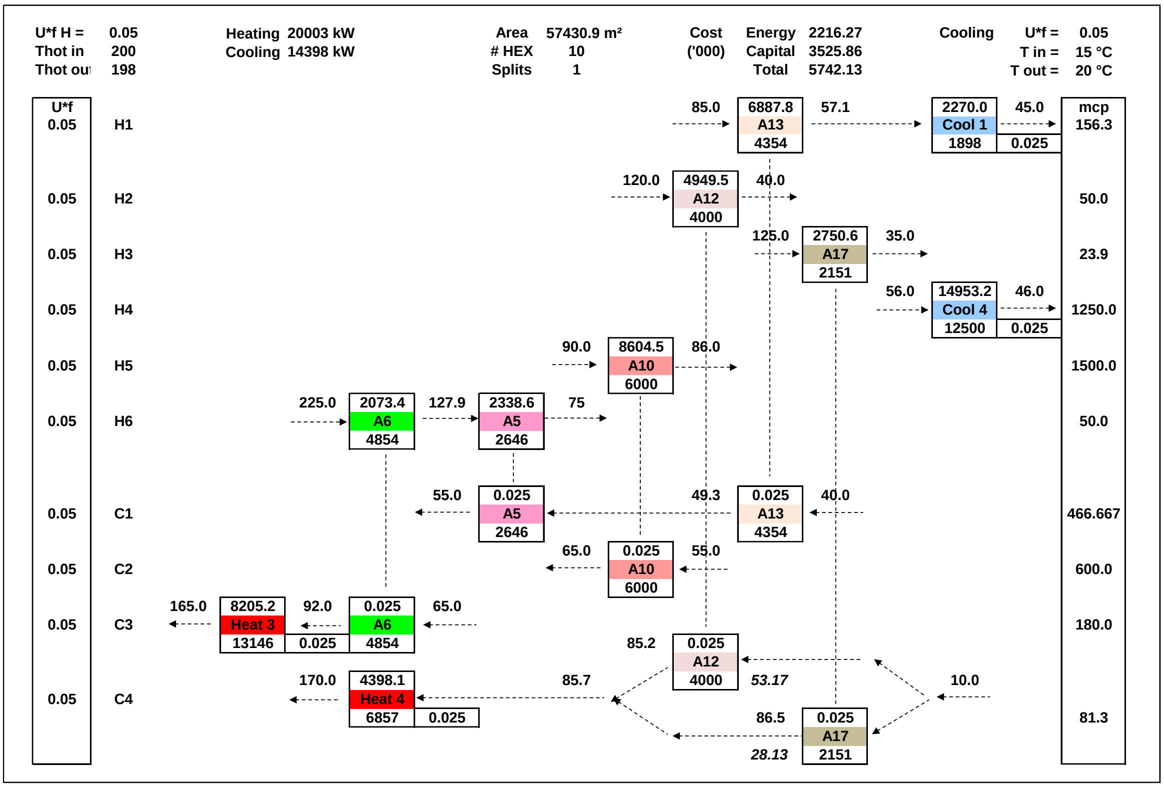

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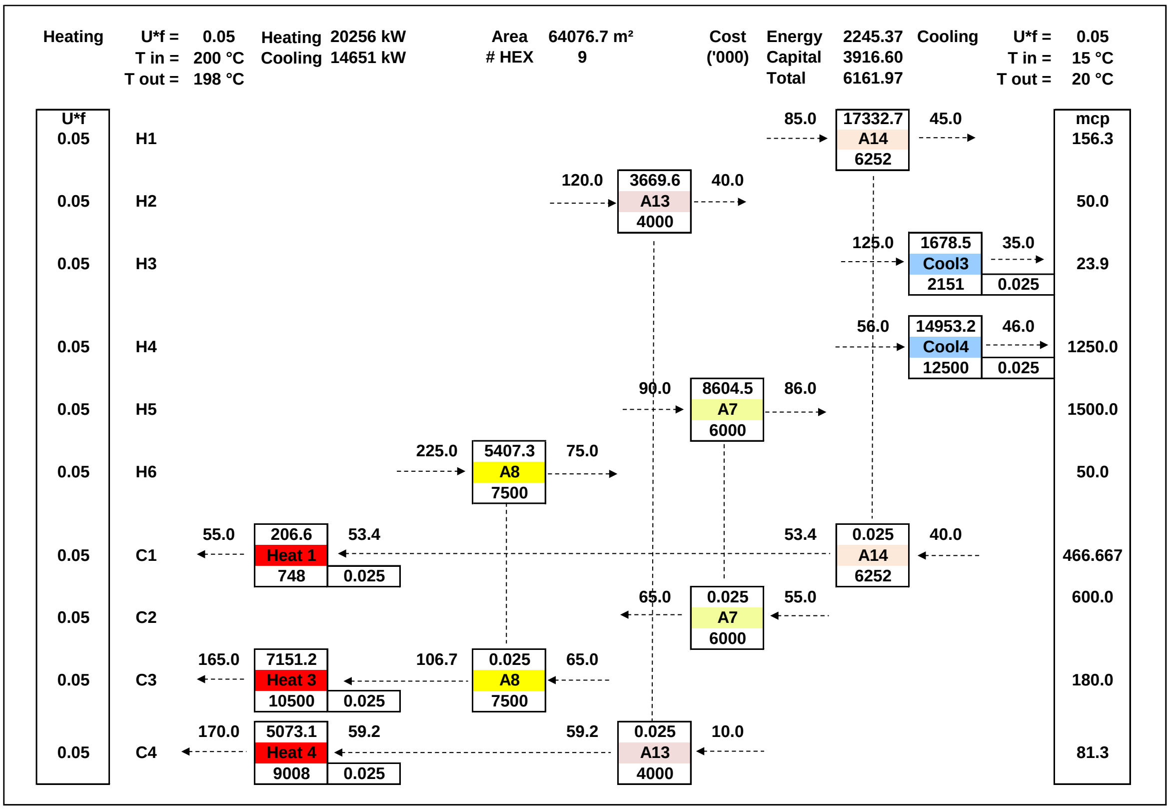


Figure 9.14

10 The 11 streams problem from Castillo – The Nitic Acid plant

The study of this Nitric Acid plant was initiated by E.Castillo [97]. It was also studied by Silva et al. [98], Stegner et al, [99], Pavão et al. [38], [77], Wang et al. [101], Xiao and Cui [102], Aguitoni et al. [7], Rathjens and Fieg [83] and Chenglin Chang et al. [9].

The data set is shown in Table 10.1. The original data set, unfortunately, contained an error in the preheating of the boiler feed water (BFW) for steam production (cold stream C4): only the BFW for the steam internally used in the plant was preheated, the preheating of the BFW for the export steam was not considered. This error has been corrected in Table 10.1.

Table 10.1

Tsupply	Ttarget	Heat	Shift	U*f	Description		mcp	Flow
°C	°C	kW	K	kW/K,m^2	-		kW/K	t/h
840	40	3991.52	5	1.5	H1	Reactor exit	4.9894	14.232
76	45	145.20	5	1.5	H2	Feed back from bleacher	4.6840	1.965
50	40	7.72	5	1.5	H3	Water to absorber	0.7720	0.664
180	77	62.799	5	1.5	H4	Condensate from steam	0.6097	0.520
180	179	292.70	5	0.8	H5	Steam for NH3 evaporation	292.7	0.520
90	45	137.97	5	1.5	H6	Water to absorber	3.066	2.600
24	25	329.80	5	0.8	C1	NH3 evaporation	329.8	0.920
25	70	24.22	5	1.5	C2	NH3 superheating	0.5383	0.920
35	122	324.25	5	1.5	C3	Off-gas reheat	3.727	12.336
90	180	493.21	5	1.5	C4	BFW preheat	5.4801	4.607
180	181	2581.10	5	0.8	C5	Steam	2581.1	4.607
20	40	885.34	5	0.8	CW	Cooling	44.267	38.063

Cost data
Heating: 110 $/kW,y Cooling: 15 $/kW,y
HEX Cost : 9094 + 485 x Area $/year

Many networks (with the original data set) have been proposed and many more are possible with a cost range between 139.232 k$/year (the network from Aguitoni in [7], revised) and 141.00 k$/year.

The published networks are interesting, but only from scientific/mathematical point of view since the link with the real process has been lost. Hot streams H4 and H5 and cold steams C4 and C5 were treated as process streams, whilst these are utilities. In terms of pinch analysis, the condensate return temperature of 77°C is a soft temperature; many networks mention a very small heat exchanger of 0.33 kW which easily can be eliminated by lowering the return temperature of the condensate from 77°C to 76.46°C. In many networks, (part of) the energy in H5 (steam) and H4 (condensate) is cooled away with cooling water, which, from energy point of view, makes no sense. No credit is taken for the exported steam.

A reference network with correct BFW preheating is shown in Figure 10.1; an optimized configuration is shown in Figure 10.2. A pinch analysis indicates that, for this threshold problem, a utility pinch is caused by the BFW preheating. A maximum of 5.354 t/h of steam can be generated which is 30% more than the existing 4.094 t/h.

A network developed with the tick-off procedure for a DTMin of 10K is shown in Figure 10.3. A heater is installed as startup heater and should not use steam during normal operation. The area (investment cost) can be reduced by accepting a split of hot stream H1 entering the pinch, leading to more vertical heat exchange and lower area, giving the network shown in Figure 10.4. Investment costs can further be reduced by merging heat exchanger units A2 and A4, obtaining an economic optimum whilst accepting a small pinch violation of 40.40 kW, as shown in Figure 10.5. The results are summarized in Table 10.2.

Table 10.2	Steam export		Energy	Capital	Revenu
	t/h	kW	k$/year	k$/year	k$/year
Reference network °)	4.094	2288.4	-238.44	120.45	117.99
Optimised configuration	4.607	2581.1	-275.97	110.3	165.67
Networks based on pinch design					
Tick-off	5.354	2999.7	-329.50	130.65	198.85
Vertical transfer	5.354	2999.7	-329.50	129.28	200.22
Economic optimum	5.294	2965.78	-325.16	117.38	207.78

°) Basis network Stegner et al. [99] without split - BFW preheat corrected

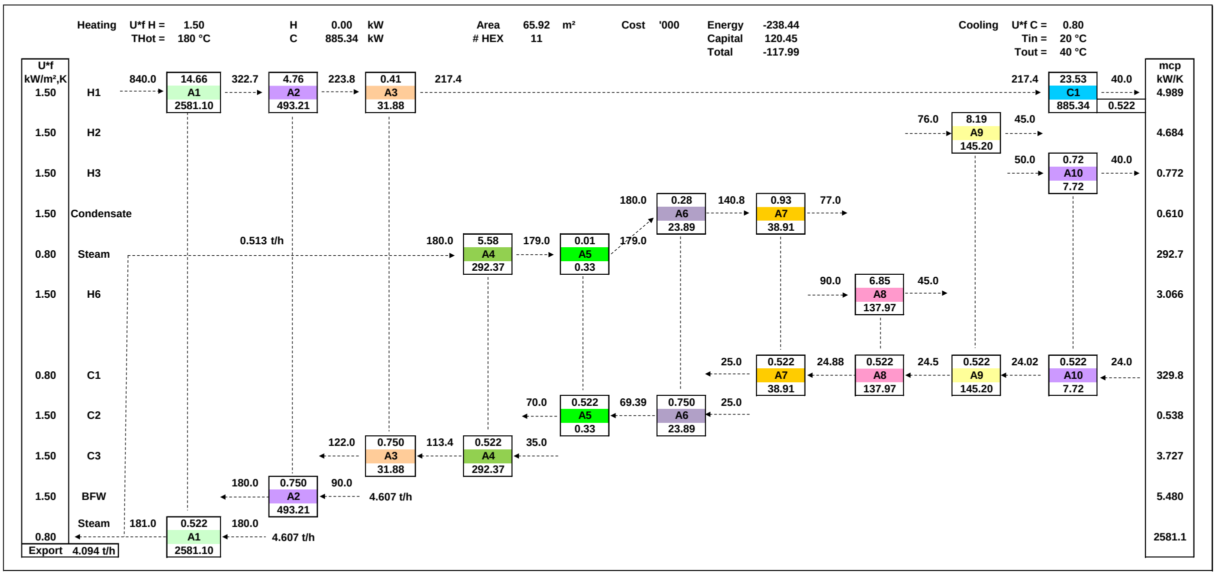


Figure 10.1

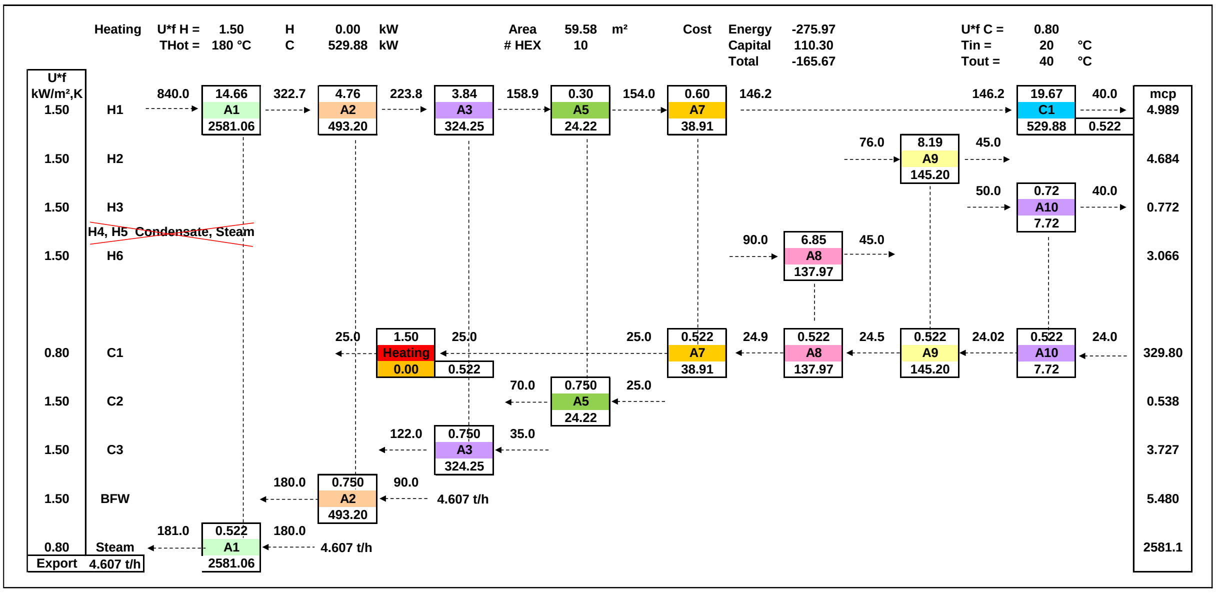


Figure 10.2

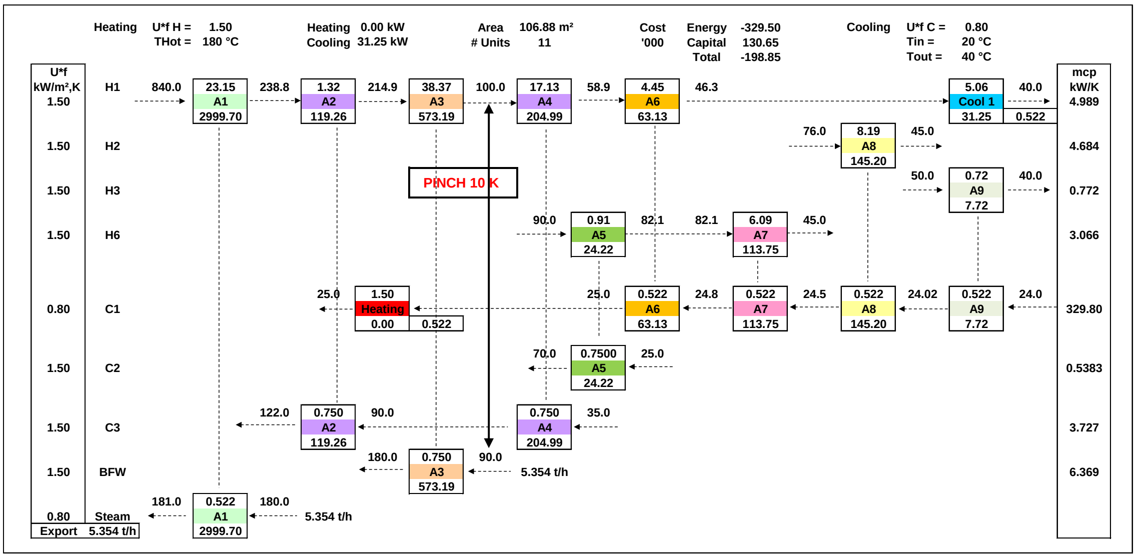


Figure 10.3

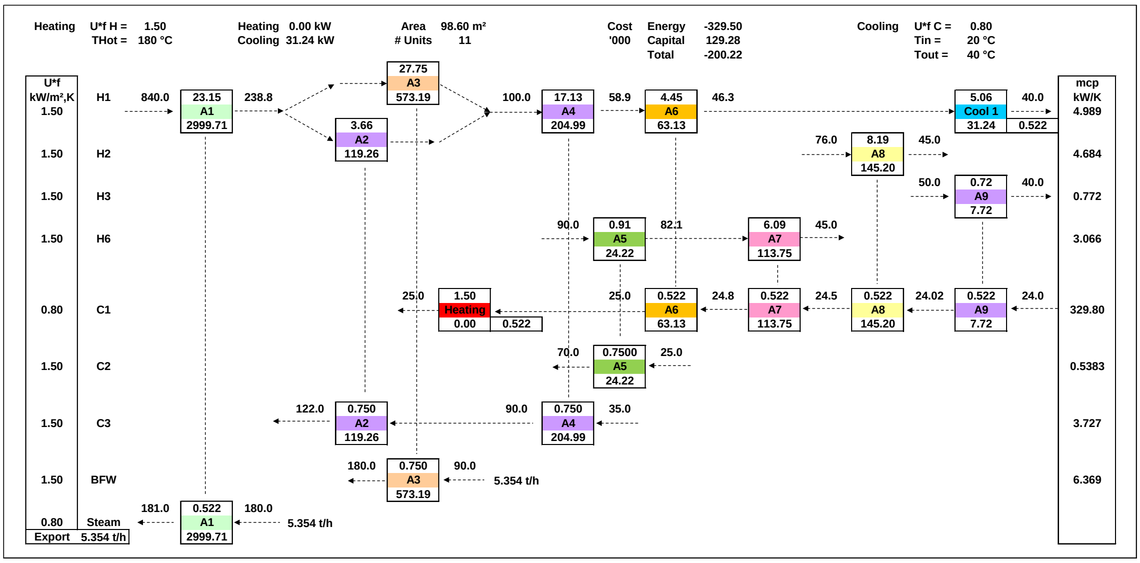
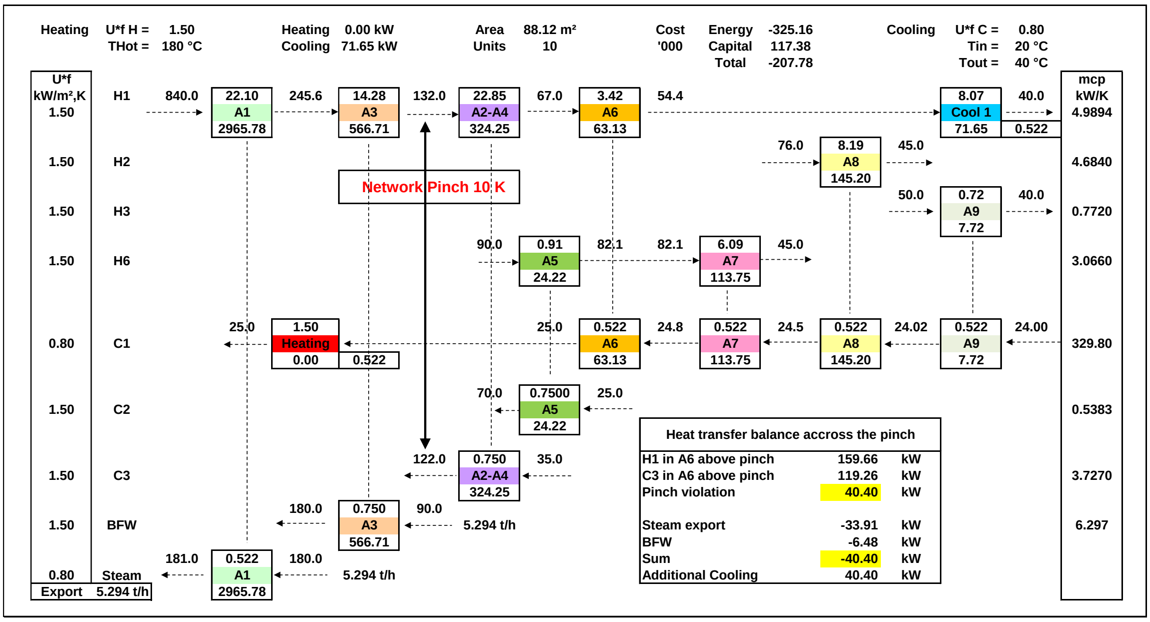


Figure 10.4



Heat transfer balance accross the pinch		
H1 in A6 above pinch	159.66	kW
C3 in A6 above pinch	119.26	kW
Pinch violation	40.40	kW
Steam export	-33.91	kW
BFW	-6.48	kW
Sum	-40.40	kW
Additional Cooling	40.40	kW

Figure 10.5

11 The 15 streams problem from Bjôrk and Pettersson

This case study was developed by Björk and Pettersson [103]. It was also studied by Björk and Nordman [104], Fieg et al. [65], Peng and Cui [74], Chen et al. [79], Pavão et al. [76], [77], [111], Wang et al. [101], Xiao an Cui [102], Escobar and Trierweiler [105], Myankooh and Shafiei [93], Ghiasvand et al. [73], Anantharaman and Gundersen [100], Rathjens and Fieg [83], Chang et al. [112], Xu et al.[113] and Caballero et al. [XXX]. It was studied by this author in [106] and revisited in [107]. The data set is shown in Table 11.1. Shift values have been optimised for minimum area for the given heat load; crisscross optimization would enable an area reduction of 3.1%.

Table 11.1

Tsupply °C	Ttarget °C	Heat kW	Shift K	U*f kW/K,m²	Descript. -
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	325	9800		1.0	Heating
25	40	7425		2.0	Cooling

Cost data

Heating: 80.0 $/kW, year Cooling 10.0 $/kW,year

HEX cost: 8000 + 500 x $\text{Area}^{0.75}$

Composite curves are shown in Figiure 11.1. For the given heating load, the pinch is caused simultaneously by hot stream H8 and cold stream C2; the curves are parallel over one third of the integration band. A pinched system would require 26 heat exchanger units whilst a single system would require only 16 units. The trade-off curve is shown in Figure 11.2. It shows a minimum between 9500 kW and 9800 kW. Target values for a single system with 9800 kW heating are a cost of 1465.31 k$/year, 16 units and an area of 3748.45 m².

The search led to an optimum network with a cost of 1492.66 k$/year; it is shown in Figure 11.3. The cost is 1.9% above target. The network has 2 independent systems since the match H7-C4 with exchanger A4 is independent. A network with one single system is shown in Figure 11.4; it has a cost of 1493.57 k$/year and 17 units. Both networks have 1 unit more than the theoretical minimum. Results can be compared in Table 11.2. During this study, more than 20 networks were developed with a lower cost than the best network published (after revision).

Table 11.2

	Heating	Area	NS °)	# HEX	# splits	Energy	Capital	Total
	kW	m²	-	-	-	k$/year	k$/year	k$/year
Björk & Pettersson	-	-	-	-	-	-	-	1513.85
Björk & Nordman	-	-	-	-	-	-	-	1530.06
Anantharaman et al. 1)	11540.0	3317.75	2	15	4	1014.85	515.9	1530.75
Fieg et al.	10615.0	4121.98	3	15	1	931.67	579.22	1510.89
Escobar and Trierweiler	9924.0	4494.89	1	17	1	869.37	635.89	1506.26
Myankooh	11114.0	4309.14	3	17	0	976.54	612.88	1589.42
Peng and Cui	10974.0	3690.80	2	17	0	963.91	573.34	1537.25
Pavao et al. 3)	10066.0	4114.00	1	19	2	882.19	624.75	1506.94
Wang et al.	10308.7	3985.98	1	19	0	904.03	615.22	1519.25
Xiao and Cui	10308.7	3918.05	1	19	0	904.03	614.94	1518.97
Chen et al.	10213.7	4046.91	1	19	0	895.48	628.25	1523.74
Ghiasvand 1), 2)	11470.0	3496.64	2	20	0	1008.55	588.44	1596.99
Rathjens and Fieg 3)	10280.3	3773.91	1	18	3	901.47	597.06	1498.54
Chang et al.	10239.5	4358.6	2	15	2	897.81	603.20	1501.00
Xu et al. 3)	9756.2	4623.22	2	16	2	854.31	640.62	1494.93
Caballero et al 3)	10050.0	4176.36	1	17	2	880.75	615.70	1496.45
This study	10235.0	3928.45	1	17	1	897.4	596.17	1493.57
	9745.0	4709.90	2	16	1	853.3	639.36	1492.66

°) Number of Independent Systems

1) Best of

2) after optimisation

3) revised

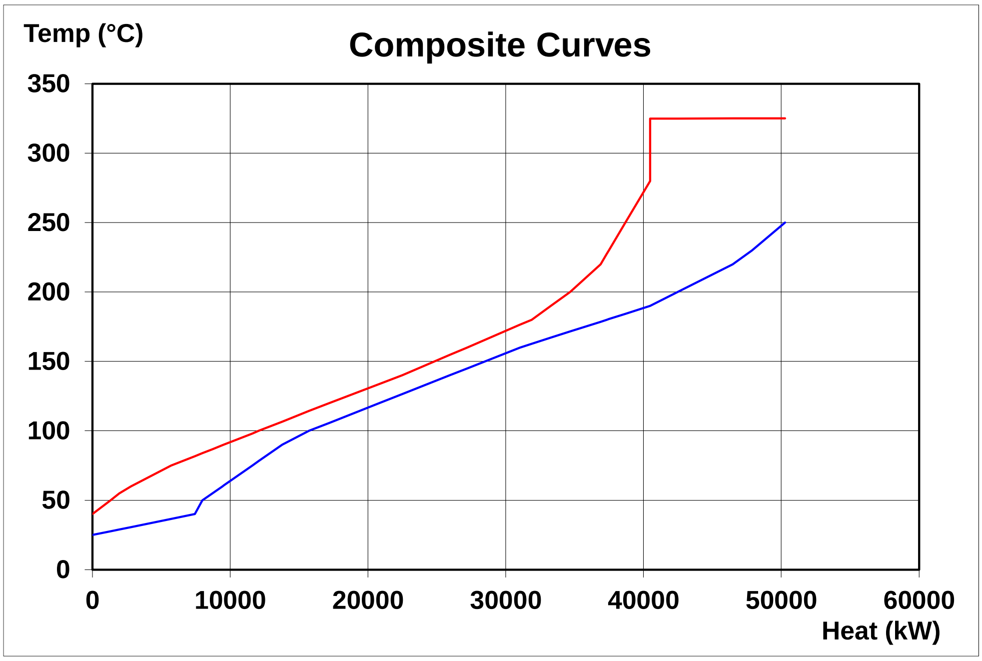


Figure 11.1

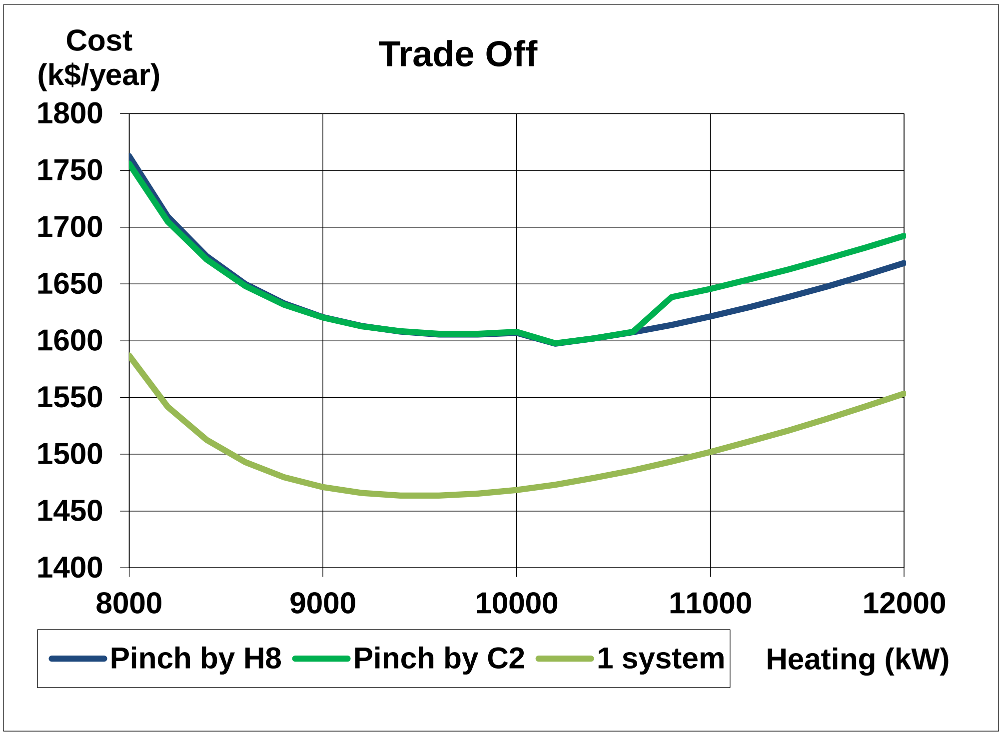


Figure 11.2

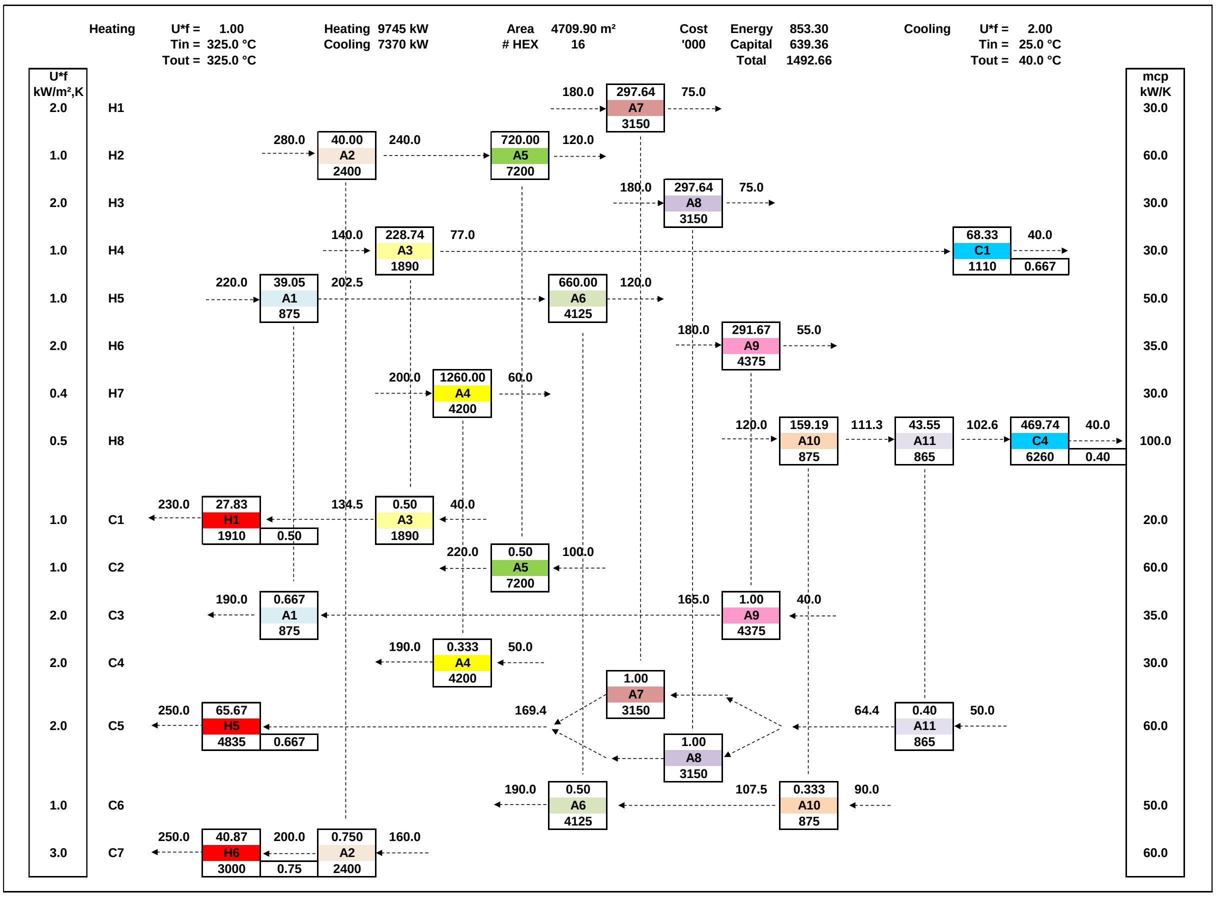


Figure 10.3

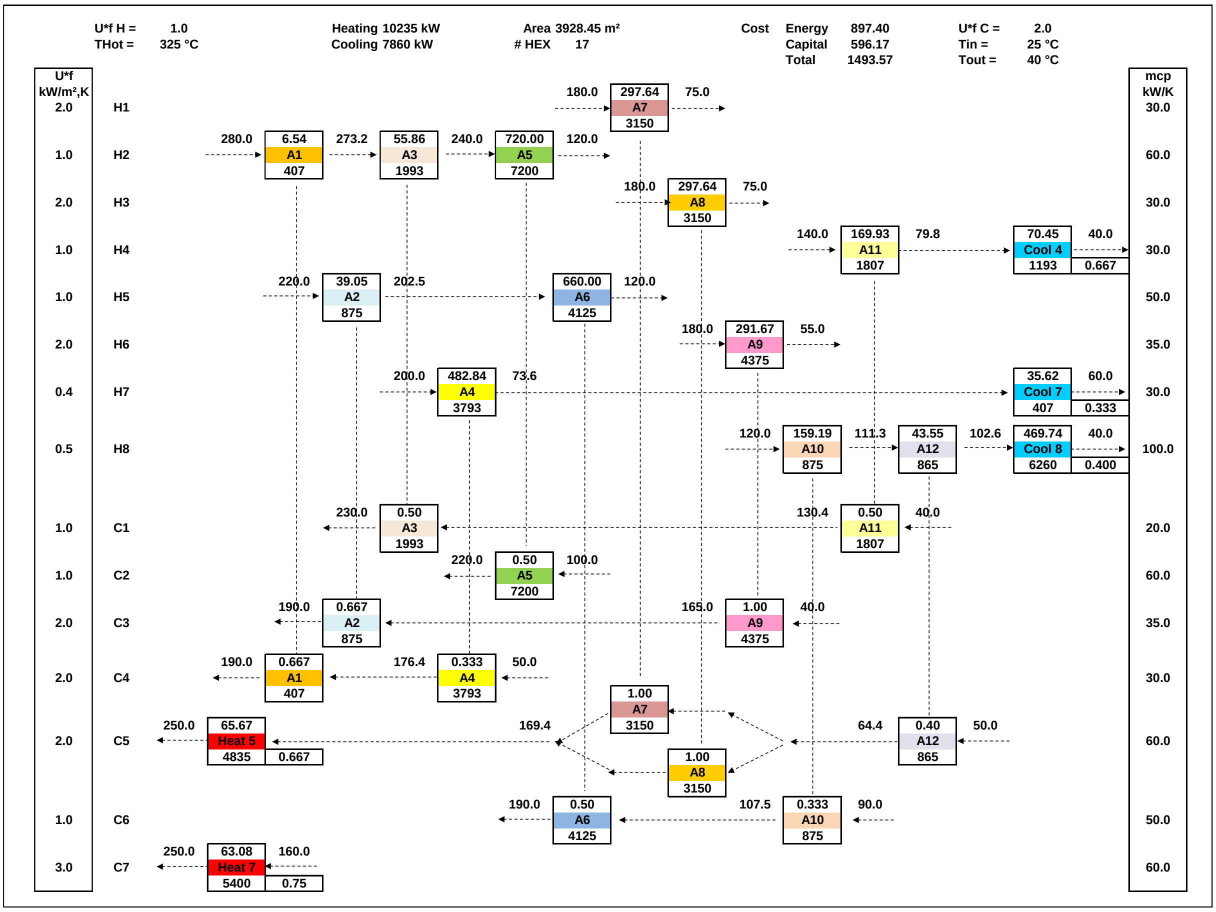

U*f H = 1.0
THot = 325 °C
Heating 10235 kW
Cooling 7860 kW
Area 3928.45 m²
HEX 17
Cost
Energy 897.40
Capital 596.17
Total 1493.57
U*f C = 2.0
Tin = 25 °C
Tout = 40 °C
U*f kW/m²,K
mcp kW/K
2.0 H1 180.0 297.64 A7 3150 75.0 30.0
1.0 H2 280.0 6.54 A1 407 273.2 55.86 A3 1993 240.0 720.00 A5 7200 120.0 60.0
2.0 H3 180.0 297.64 A8 3150 75.0 30.0
1.0 H4 140.0 169.93 A11 1807 79.8 70.45 Cool 4 1193 40.0 0.667 30.0
1.0 H5 220.0 39.05 A2 875 202.5 660.00 A6 4125 120.0 50.0
2.0 H6 180.0 291.67 A9 4375 55.0 35.0
0.4 H7 200.0 482.84 A4 3793 73.6 35.62 Cool 7 407 60.0 0.333 30.0
0.5 H8 120.0 159.19 A10 875 111.3 43.55 A12 865 102.6 469.74 Cool 8 6260 40.0 0.400 100.0
1.0 C1 230.0 0.50 A3 1993 130.4 0.50 A11 1807 40.0 20.0
1.0 C2 220.0 0.50 A5 7200 100.0 60.0
2.0 C3 190.0 0.667 A2 875 165.0 1.00 A9 4375 40.0 35.0
2.0 C4 190.0 0.667 A1 407 176.4 0.333 A4 3793 50.0 30.0
2.0 C5 250.0 65.67 Heat 5 4835 0.667 169.4 1.00 A7 3150 1.00 A8 3150 64.4 0.40 A12 865 50.0 60.0
1.0 C6 190.0 0.50 A6 4125 107.5 0.333 A10 875 90.0 50.0
3.0 C7 250.0 63.08 Heat 7 5400 0.75 160.0 60.0

Figure 10.4

12 The Bandar Iman Aromatics Plant

This case was developed by Khorasany and Fesanghary [90]. It has been studied by many authors among which Huo et al.[72], Pavão et al. [76], [78], [111], Zhang et al. [74], Chen et al [79], Aguitoni et al. [7], Bao et al. [48], Zhang and Cui [32], Brand et al. [109], Gorji-Bandpy et al. [94], Nair and Karimi [110], Rathjens and Fieg [83], Xu et al. [82] and Caballero et al. [10], It was also studied by this author [108].

The data set is shown in Table 12.1. In the utility data of the original study, apparently, temperatures for steam and cooling water were given in K instead of °C; this was corrected. Shift values in Table 12.1 have been optimized for minimum area for a heating load of 9950 kW, corresponding with the minimum cost in the Trade-off curve in Figure 12.2. Composite curves are shown in Figure 12.1.

Table 12.1

Tsupply	Ttarget	Heat	Optim shift	U*f	Descript.
°C	°C	kW	K	kW/K,m²	K
385.0	159.0	29 721.3	-26	1.238	H1
516.0	43.0	567 108.1	4	0.546	H2
132.0	82.0	18 926.0	0	0.771	H3
91.0	60.0	18 275.9	1	0.859	H4
217.0	43.0	32 401.6	2	1.000	H5
649.0	43.0	70 296.0	0	1.000	H6
30.0	385.0	42 280.5	-1	1.850	C1
99.0	471.0	71 070.6	3	1.129	C2
437.0	521.0	31 744.4	4	0.815	C3
78.0	418.6	54 642.5	8	1.000	C4
217.0	234.0	22 060.9	46	0.443	C5
256.0	266.0	27 530.0	-6	2.085	C6
49.0	149.0	19 739.0	0	1.000	C7
59.0	163.4	12 857.5	-1	1.063	C8
163.0	649.0	46 646.3	0	1.810	C9
219.0	221.3	4 594.3	1	1.377	C10
1800.0	800.0	8 700.0		1.200	Flue gas
236.0	236.0	0.0		1.000	Steam
38.0	82.0	412 262.9		1.000	CW

Cost data

Flue gas: 35.0 $/kW,year; Steam: 27.0 $/kW,year; Cooling Water 2.1 $/kW,year

Annual HEX cost: 26 600 + 4147.5 x $A^{0.6}$ $/year

The pinch is caused by hot stream H2. Target cost is 7804.85 for a network with 19 units (2 systems), alternatively 7666.06 k$/year for a network with 17 units (1 system).

The best network with 2 heaters has a cost of 6630.33 k$/year; it is shown in Figure 12.4, the best network with 1 heater has a cost of 6642.28 $/year and is shown in Figure 12.5. The results are significantly better than estimated by the analysis. The reason is the large differences between the heat exchanger areas whilst the analysis assumes equal areas, combined with the relatively low exponent in the exchanger cost function.

The shape of the Grand Composite (Figure 12.3) would suggest a potential for recovery of up to 150 MW of steam, the optimum value depending upon economics. Networks were developed for recovery of steam at a temperature of 240°C, giving a margin of 4K with the utility steam at 236 K. The credit for the steam recovered was set as the cost for offtake of steam (27.0 $/kW,year). Boiler feed water was assumed to be available at 90°C.

The networks without steam recovery were taken as a basis and an additional split was introduced on hot stream H2 to accommodate the steam recovery. The resulting networks are shown in Figure 12.6, respectively Figure 12.7. It was possible to recover up to 289 t/h (143 MW) of 33 bar steam. Cooling water requirements dropped by 58%.

The results can be compared with published results in Table 12.2 and Table 12.3. Some published results could not be checked because of lack of details, some others had no optimized stream splits or different cooling water temperatures; many networks required review. All published networks with 2 heaters have parallel heaters in the flue gas track; since splitting a flue gas stream is not obvious, this is not best practice - unless required by the cold stream temperatures. The proposed networks have serial heaters in the flue gas track. The network with 1 heater can be derived from the network with 2 heaters by replacing heater Heat 3 by heat exchanger A2 in Figure 12.5 and further development with incremental evolution. The network of Caballero et al. with 1 heater [10], the cheapest network published so far, has the same structure as the network in Figure 12.5, but one more split and is 119 $/year cheaper, which, however, would not compensate for the real cost of an additional split.

Table 12.2

		Heating	Area	# units	# splits	Energy	Capital	Total
Authors		kW	m^2	-	-	'000 $/y	'000 $/y	'000 $/y
Khorasany et al. (2009)		66 070	n.a.	18	2	n.a.	n.a.	7 435.74
Gorji-Bandpy et al. (2011)		77 550	n.a.	18	4	n.a.	n.a.	7 178.79
Brandt et al. (2011) °)		8 014	31 838	18	3	1 144.80	5 655.08	6 799.88
Huo Zhaoyi et al.(2012)		35 140	28 475	17	0	2 151.18	5 072.72	7 223.90
Wang (2016)		11 534	31 661	18	0	1 275.39	5 693.69	6 969.08
Zhang et al. (2017) °)		23 794	29 768	19	0	1 730.23	5 481.88	7 212.12
Chen et al. (2017) °)		14 328	30 787	19	0	1 379.06	5 637.42	7 016.48
Aguitoni et al. (2018) °)		33 877	28 259	17	4	2 104.32	4 998.47	7 102.79
Zhang and Cui (2018)		10 626	31 397	18	0	1 241.69	5 619.42	6 861.11
Pavão et al. (2018) °)		9 498	31 013	18	5	1 199.86	5 512.88	6 712.74
Nair et al. (2019)		8 689	30 669	19	7	1 169.83	5 526.07	6 695.90
Rathjens and Fieg (2019) °)		9 710	30 806	18	6	1 207.71	5 450.05	6 657.75
Xu et al. (2020) °)		9 666	30 808	18	5	1 206.08	5 446.10	6 652.18
Caballero et al. (2021) °)		8 741	30 623	18	4	1 171.77	5 470.39	6 642.16

°) revised by the author

This work								
Base case	2 heaters	9 772	30 650	18	3	1 210.02	5 420.31	6 630.33
	1 heater	8 716	30 632	18	3	1 170.85	5 471.44	6 642.28
With steam recovery	2 heaters	34 234	39 437	19	4	-2 186.58	6 719.94	4 533.36
	1 heater	16 917	40 403	20	4	-2 428.02	7 117.22	4 689.20

Table 12.3

Impact of recovery of saturated 33 bar steam						
Additional heat input		Steam recovered		CW savings	Savings vs. base case	
	kW	kW	t/h	kW	'000 $/y	%
2 heaters	24 462	143 603	289.05	174 957	2 096.97	32%
1 heater	8 201	130 495	262.12	172 638	1 953.08	29%

Figure 12.1

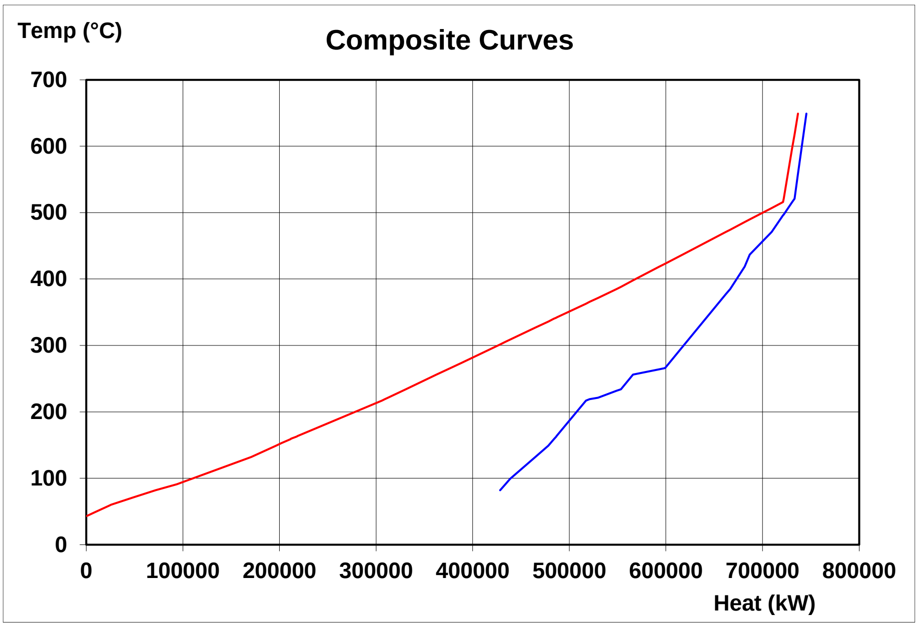


Figure 12.2

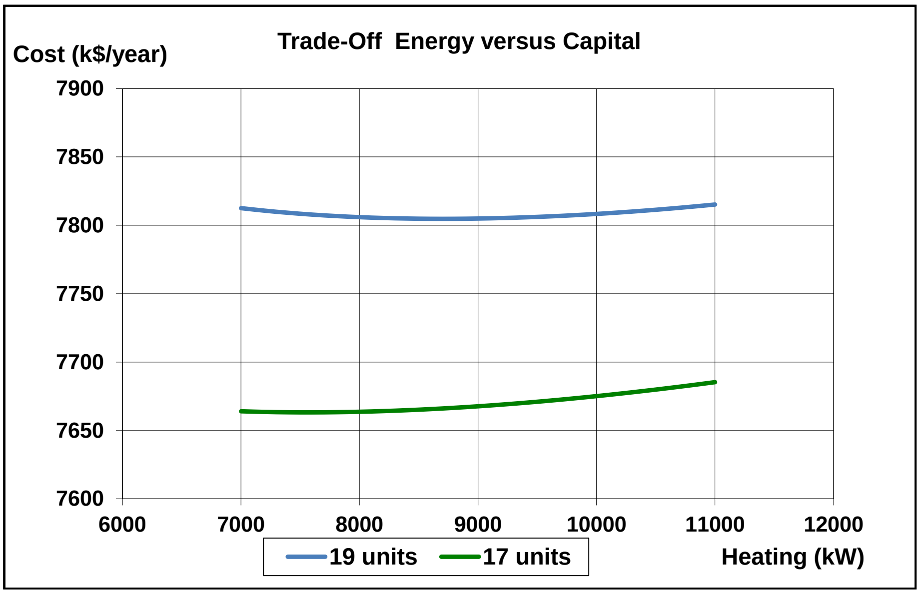
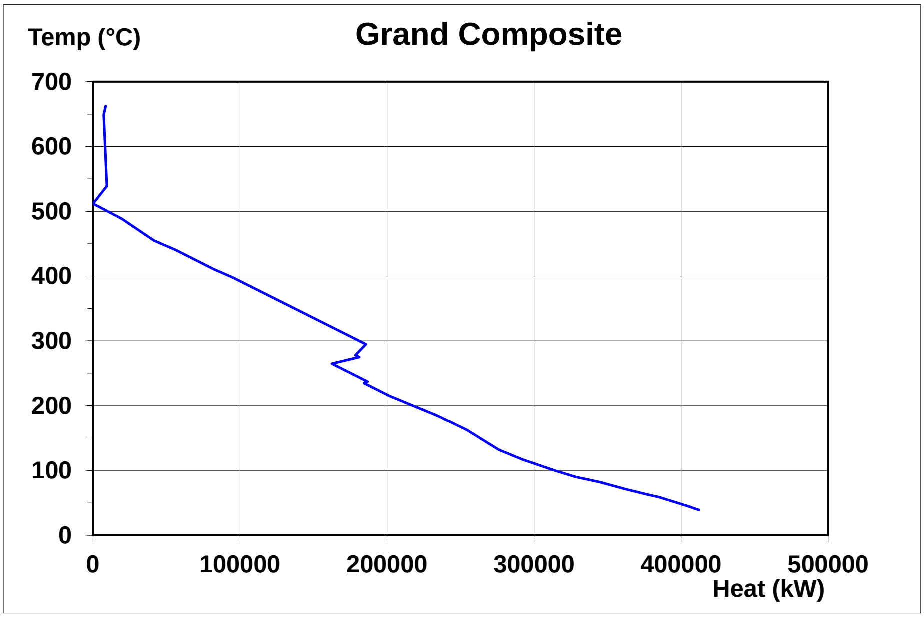


Figure 12.3



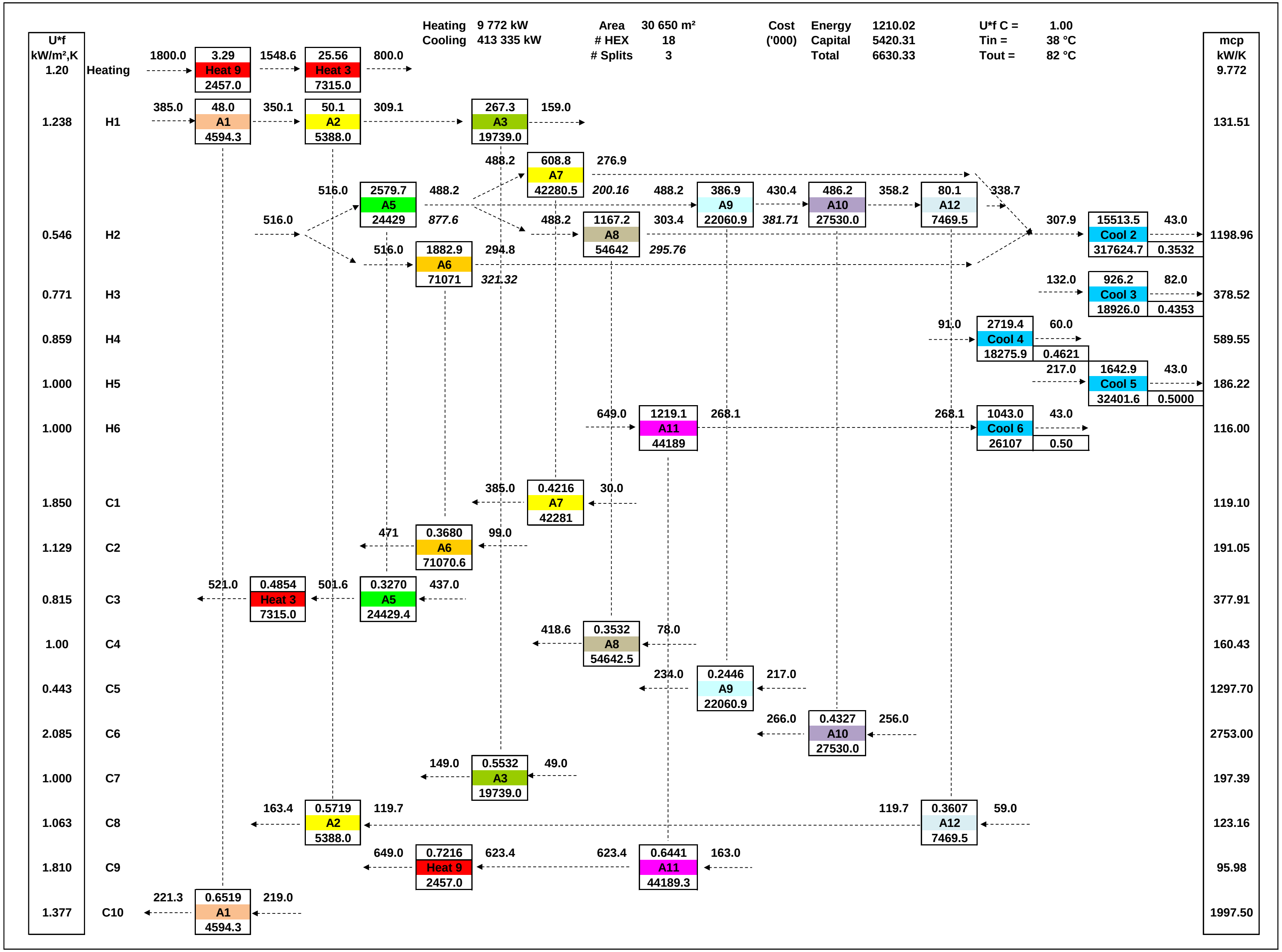

Heating 9 772 kW
Cooling 413 335 kW
Area 30 650 m²
HEX 18
Splits 3
Cost ('000)
Energy 1210.02
Capital 5420.31
Total 6630.33
U*f C = 1.00
Tin = 38 °C
Tout = 82 °C
U*f kW/m²,K
mcp kW/K
1.20 Heating 9.772
1.238 H1 131.51
0.546 H2 1198.96
0.771 H3 378.52
0.859 H4 589.55
1.000 H5 186.22
1.000 H6 116.00
1.850 C1 119.10
1.129 C2 191.05
0.815 C3 377.91
1.00 C4 160.43
0.443 C5 1297.70
2.085 C6 2753.00
1.000 C7 197.39
1.063 C8 123.16
1.810 C9 95.98
1.377 C10 1997.50
1800.0 3.29 Heat 9 2457.0 1548.6 25.56 Heat 3 7315.0 800.0
385.0 48.0 A1 4594.3 350.1 50.1 A2 5388.0 309.1 267.3 A3 19739.0 159.0
488.2 608.8 A7 42280.5 276.9
516.0 2579.7 A5 24429 488.2 877.6
200.16 488.2 386.9 A9 22060.9 430.4 486.2 A10 27530.0 358.2 80.1 A12 7469.5 338.7
516.0 488.2 1167.2 A8 54642 303.4 381.71 295.76
307.9 15513.5 Cool 2 317624.7 0.3532 43.0
516.0 1882.9 A6 71071 294.8 321.32
132.0 926.2 Cool 3 18926.0 0.4353 82.0
91.0 2719.4 Cool 4 18275.9 0.4621 60.0
217.0 1642.9 Cool 5 32401.6 0.5000 43.0
649.0 1219.1 A11 44189 268.1
268.1 1043.0 Cool 6 26107 0.50 43.0
385.0 0.4216 A7 42281 30.0
471 0.3680 A6 71070.6 99.0
521.0 0.4854 Heat 3 7315.0 501.6 0.3270 A5 24429.4 437.0
418.6 0.3532 A8 54642.5 78.0
234.0 0.2446 A9 22060.9 217.0
266.0 0.4327 A10 27530.0 256.0
149.0 0.5532 A3 19739.0 49.0
163.4 0.5719 A2 5388.0 119.7
119.7 0.3607 A12 7469.5 59.0
649.0 0.7216 Heat 9 2457.0 623.4
623.4 0.6441 A11 44189.3 163.0
221.3 0.6519 A1 4594.3 219.0

Figure 12.4

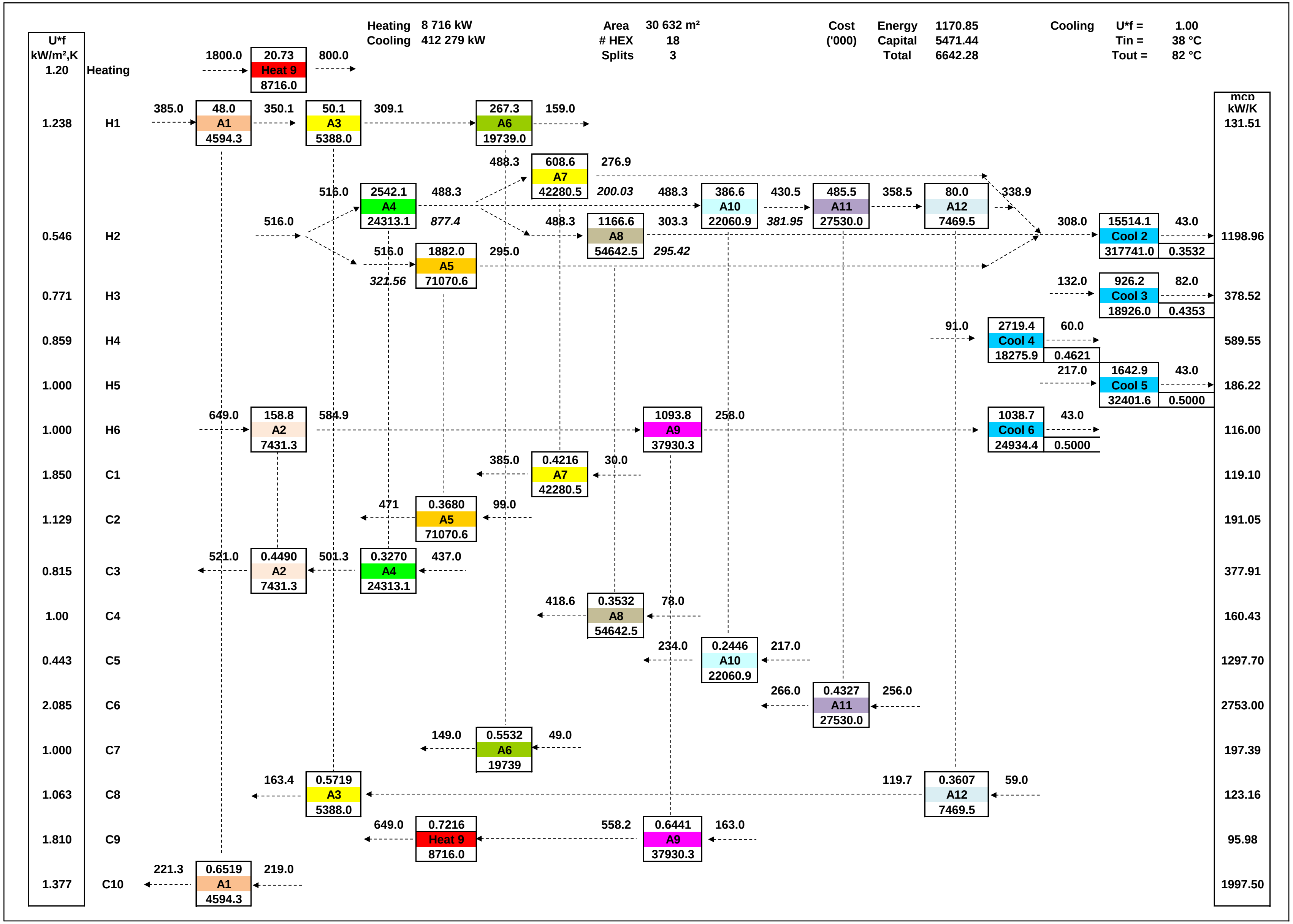
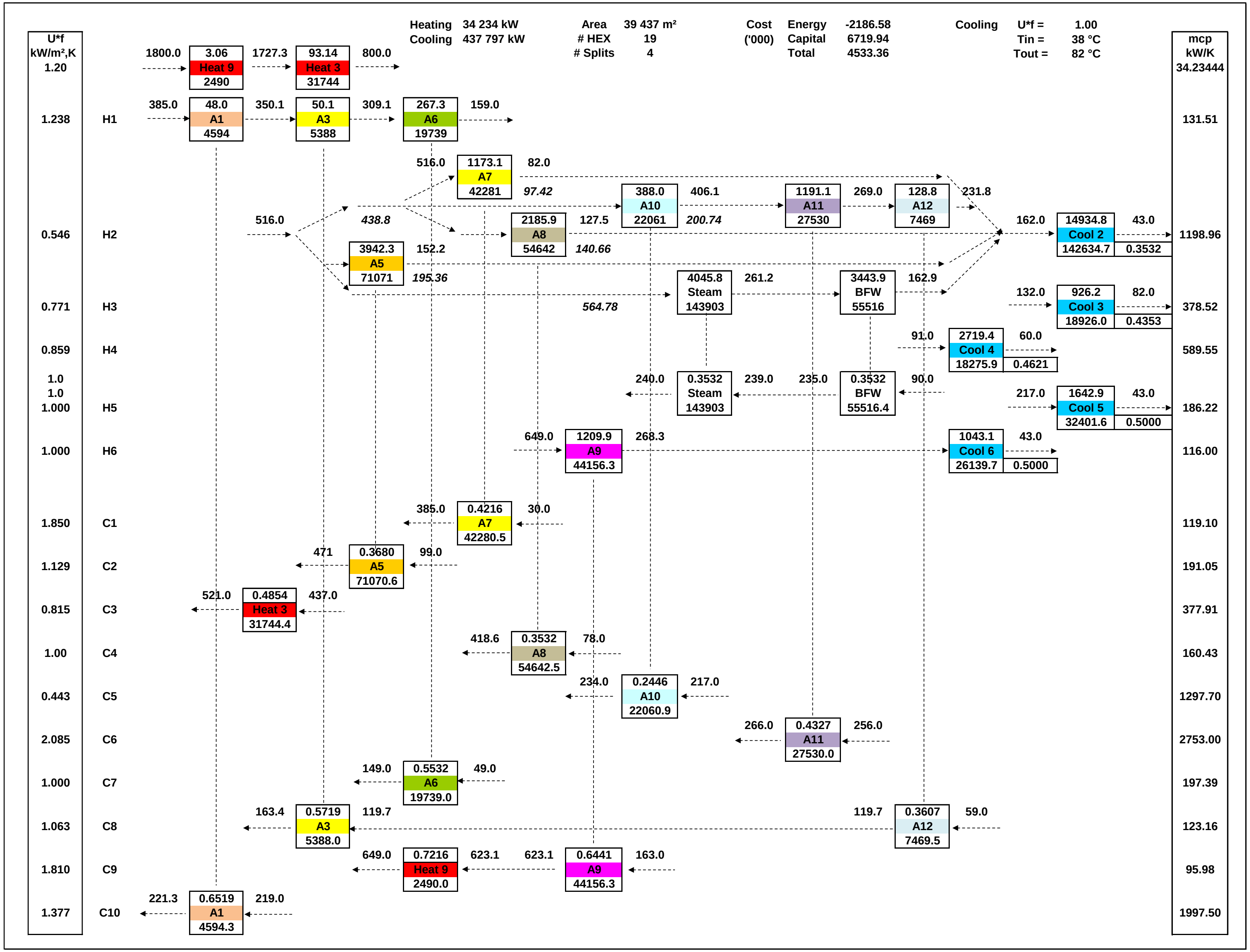

Heating 8 716 kW
Cooling 412 279 kW
Area 30 632 m²
HEX 18
Splits 3
Cost ('000)
Energy 1170.85
Capital 5471.44
Total 6642.28
Cooling U*f = 1.00
Tin = 38 °C
Tout = 82 °C
U*f kW/m²,K
1.20
Heating
1800.0
20.73
Heat 9
8716.0
800.0
mcp kW/K
1.238
H1
385.0
48.0
A1
4594.3
350.1
50.1
A3
5388.0
309.1
267.3
A6
19739.0
159.0
131.51
488.3
608.6
A7
42280.5
276.9
516.0
2542.1
A4
24313.1
488.3
200.03
488.3
386.6
A10
22060.9
430.5
485.5
A11
27530.0
358.5
80.0
A12
7469.5
338.9
0.546
H2
516.0
877.4
488.3
1166.6
A8
54642.5
303.3
381.95
308.0
15514.1
Cool 2
317741.0
43.0
0.3532
1198.96
516.0
1882.0
A5
71070.6
295.0
295.42
321.56
0.771
H3
132.0
926.2
Cool 3
18926.0
82.0
0.4353
378.52
0.859
H4
91.0
2719.4
Cool 4
18275.9
60.0
0.4621
589.55
1.000
H5
217.0
1642.9
Cool 5
32401.6
43.0
0.5000
186.22
1.000
H6
649.0
158.8
A2
7431.3
584.9
1093.8
A9
37930.3
258.0
1038.7
Cool 6
24934.4
43.0
0.5000
116.00
1.850
C1
385.0
0.4216
A7
42280.5
30.0
119.10
1.129
C2
471
0.3680
A5
71070.6
99.0
191.05
0.815
C3
521.0
0.4490
A2
7431.3
501.3
0.3270
A4
24313.1
437.0
377.91
1.00
C4
418.6
0.3532
A8
54642.5
78.0
160.43
0.443
C5
234.0
0.2446
A10
22060.9
217.0
1297.70
2.085
C6
266.0
0.4327
A11
27530.0
256.0
2753.00
1.000
C7
149.0
0.5532
A6
19739
49.0
197.39
1.063
C8
163.4
0.5719
A3
5388.0
119.7
0.3607
A12
7469.5
59.0
123.16
1.810
C9
649.0
0.7216
Heat 9
8716.0
558.2
0.6441
A9
37930.3
163.0
95.98
1.377
C10
221.3
0.6519
A1
4594.3
219.0
1997.50

Figure 12.5

Figure 12.6


Heating 34 234 kW
Cooling 437 797 kW
Area 39 437 m²
HEX 19
Splits 4
Cost ('000)
Energy -2186.58
Capital 6719.94
Total 4533.36
Cooling
U*f = 1.00
Tin = 38 °C
Tout = 82 °C
U*f kW/m²,K
1.20
mcp kW/K
34.23444
1800.0
3.06
Heat 9
2490
1727.3
93.14
Heat 3
31744
800.0
1.238
H1
385.0
48.0
A1
4594
350.1
50.1
A3
5388
309.1
267.3
A6
19739
159.0
131.51
516.0
1173.1
A7
42281
82.0
97.42
388.0
A10
22061
406.1
1191.1
A11
27530
269.0
128.8
A12
7469
231.8
0.546
H2
516.0
438.8
2185.9
A8
54642
127.5
200.74
162.0
14934.8
Cool 2
142634.7
0.3532
43.0
1198.96
3942.3
A5
71071
152.2
140.66
195.36
4045.8
Steam
143903
261.2
3443.9
BFW
55516
162.9
0.771
H3
564.78
132.0
926.2
Cool 3
18926.0
0.4353
82.0
378.52
0.859
H4
91.0
2719.4
Cool 4
18275.9
0.4621
60.0
589.55
1.0
1.0
1.000
H5
240.0
0.3532
Steam
143903
239.0
235.0
0.3532
BFW
55516.4
90.0
217.0
1642.9
Cool 5
32401.6
0.5000
43.0
186.22
1.000
H6
649.0
1209.9
A9
44156.3
268.3
1043.1
Cool 6
26139.7
0.5000
43.0
116.00
1.850
C1
385.0
0.4216
A7
42280.5
30.0
119.10
1.129
C2
471
0.3680
A5
71070.6
99.0
191.05
0.815
C3
521.0
0.4854
Heat 3
31744.4
437.0
377.91
1.00
C4
418.6
0.3532
A8
54642.5
78.0
160.43
0.443
C5
234.0
0.2446
A10
22060.9
217.0
1297.70
2.085
C6
266.0
0.4327
A11
27530.0
256.0
2753.00
1.000
C7
149.0
0.5532
A6
19739.0
49.0
197.39
1.063
C8
163.4
0.5719
A3
5388.0
119.7
119.7
0.3607
A12
7469.5
59.0
123.16
1.810
C9
649.0
0.7216
Heat 9
2490.0
623.1
623.1
0.6441
A9
44156.3
163.0
95.98
1.377
C10
221.3
0.6519
A1
4594.3
219.0
1997.50

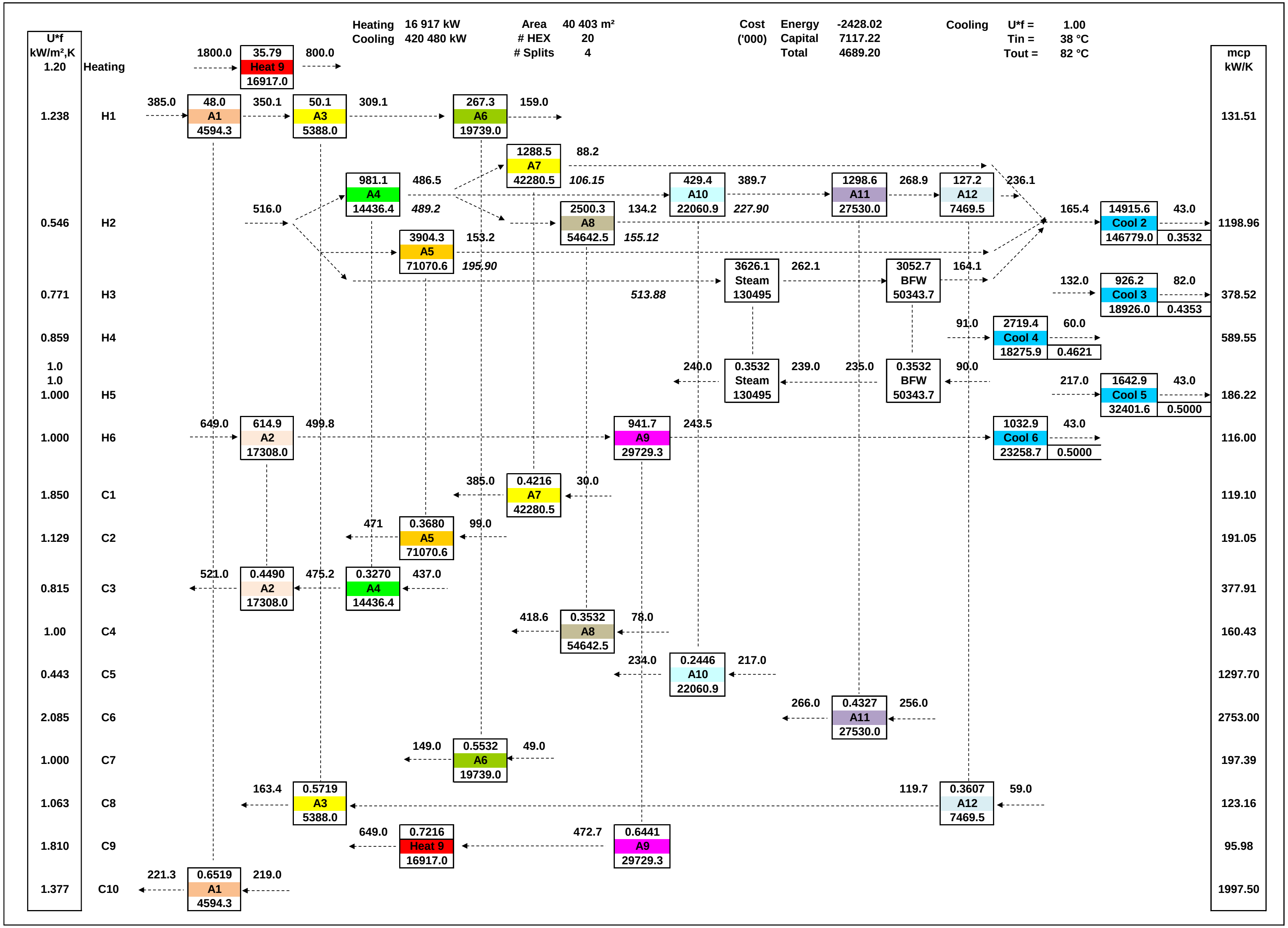

Heating 16 917 kW
Cooling 420 480 kW
Area 40 403 m²
HEX 20
Splits 4
Cost ('000)
Energy -2428.02
Capital 7117.22
Total 4689.20
Cooling U*f = 1.00
Tin = 38 °C
Tout = 82 °C
U*f kW/m²,K
1.20
Heating
1800.0
35.79
Heat 9
16917.0
800.0
mcp kW/K
1.238
H1
385.0
48.0
A1
4594.3
350.1
50.1
A3
5388.0
309.1
267.3
A6
19739.0
159.0
131.51
1288.5
A7
42280.5
88.2
106.15
981.1
A4
14436.4
486.5
489.2
429.4
A10
22060.9
389.7
227.90
1298.6
A11
27530.0
268.9
127.2
A12
7469.5
236.1
0.546
H2
516.0
2500.3
A8
54642.5
134.2
155.12
165.4
14915.6
Cool 2
146779.0
43.0
0.3532
1198.96
3904.3
A5
71070.6
153.2
195.90
3626.1
Steam
130495
262.1
3052.7
BFW
50343.7
164.1
0.771
H3
513.88
132.0
926.2
Cool 3
18926.0
82.0
0.4353
378.52
0.859
H4
91.0
2719.4
Cool 4
18275.9
60.0
0.4621
589.55
1.0
1.0
1.000
H5
240.0
0.3532
Steam
130495
239.0
235.0
0.3532
BFW
50343.7
90.0
217.0
1642.9
Cool 5
32401.6
43.0
0.5000
186.22
1.000
H6
649.0
614.9
A2
17308.0
499.8
941.7
A9
29729.3
243.5
1032.9
Cool 6
23258.7
43.0
0.5000
116.00
1.850
C1
385.0
0.4216
A7
42280.5
30.0
119.10
1.129
C2
471
0.3680
A5
71070.6
99.0
191.05
0.815
C3
521.0
0.4490
A2
17308.0
475.2
0.3270
A4
14436.4
437.0
377.91
1.00
C4
418.6
0.3532
A8
54642.5
78.0
160.43
0.443
C5
234.0
0.2446
A10
22060.9
217.0
1297.70
2.085
C6
266.0
0.4327
A11
27530.0
256.0
2753.00
1.000
C7
149.0
0.5532
A6
19739.0
49.0
197.39
1.063
C8
163.4
0.5719
A3
5388.0
119.7
0.3607
A12
7469.5
59.0
123.16
1.810
C9
649.0
0.7216
Heat 9
16917.0
472.7
0.6441
A9
29729.3
95.98
1.377
C10
221.3
0.6519
A1
4594.3
219.0
1997.50

Figure 12.7

13 The 20 streams problem from Xing Luo (10H10C)

Case 10 is a larger scale example with 10 hot streams, 10 cold streams, 1 hot and 1cold utility.

It was originally set up by Wu Xiao et al. for illustrating a new procedure based on Stream Pseudo Temperatures [120]. They developed a network using multi-stream heat exchangers.

The example was then used by Xing Luo et al. [65] for illustrating the capabilities of a hybrid genetic algorithm for synthesis of heat exchanger networks. Thereafter, it was also studied by Laukkanen et al. [36], [67], Liang et al. [119], Zhang et al [118], [116], Pavao et al. [76], [77], Yuan Xiao et al. [80], Rathjens and Fieg [83], Xu et al [113], Caballero et al. [10] and Xianli Wu et al. [117]. The case was also studied by this author [121].

Stream and cost data are given in Table 13.1.

Table 13.1

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

Cost data

Heating 70.0$/kW,year ; Cooling 10.0$/kW,year

Annual HEX cost = 8000 + 800 x $A^{0.8}$ $/year

°) Stream pseudo temperature method and using multistream HEX

Next to the shift values used by Wu Xiao, also optimum shift values using crisscross optimisation for a heat input of 8.75 MW are shown in Table 13.1.

Balanced Composite Curves are shown in Figure 13.1. The curves are parallel over a broad range with an unclear pinch caused by streams H4, C2 and C8 almost simultaneously. The Grand Composite is shown in Figure 13.2. It suggests a potential for roughly 3 MW low temperature heat as hot utility, say, as hot water 90°C to 50°C. This, however, would require recalculation of optimum shift values and would more than double the investment cost, which would not be compensated by lower energy cost.
Trade-off between energy and capital cost is shown in Figure 13.3, for shift values for hot stream H6 of 30 K and 124 K. The network was treated as a single system, requiring 21 units, whilst a pinch based design with 2 systems, segregated at the pinch, would require 36 units. The impact of the differences in heat transfer values on required surface area and resulting cost is significant and offers ample opportunities for crisscross. The effect of shifting hot stream H6 is impressive and enables the required surface area to be reduced by 30% (Figure 13.4). The effect on the area cost is shown in Figure 13.5. For shift values above 30 K, heating requirement goes up with 940 kW for a shift of 124 K which, however, is overcompensated by the drop in area cost.

With crisscross analysis, the energy target is 20% lower and the cost target is 14% lower than with classic analysis. As demonstrated by the various such networks that were developed, that much lower cost target is also achievable. 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 whilst classic pinch analysis would have suggested to integrating 75% of that heat load with cold streams.

The main problem during the first study [121] arising after processing the data from the grid using LP was the very large number of heat exchanger units to deal with in a final optimisation program using incremental evolution on a data set with composite curves that were parallel over a broad integration span. The problem was revisited, using a more sophistcated approach.

With the view to minimising the number of units, heuristics were applied such as:

- Check wheter the smallest heat load can be satisfied with a single heat exchanger unit;
- Check whether matches are possible between streams with similar mcp's in parallel sections of the composite curves;
- Check whether matches are possible between streams crossing the pinch without violating pinch design rules;
- In view of avoiding stream splitting at the pinch, check whether there is a 'near' pinch close to the pinch; it might be advantageous to start the design at the 'near' pinch instead of at the pinch.

The size of the problem was reduced with the following steps:

- Following the original analysis, hot stream H6 is put on a cooler,
- Cold stream C6 (the smallest heat load) is matched with hot stream H5 (match on streams both with very low U*f, taking advantage of the cost structure); as can be seen from the grid data, the pinch violation is minimal,
- The residue of hot stream H5 (1400 kW, the smallest remaining heat load with a small U*f) is matched with cold stream C10 (the stream with the lowest U*f),
- The residue of cold stream C10 (400 kW) is set side as part of the remaining problem,

- Hot stream H8 (the biggest hot stream) is ticked off against the cold side of C3 (biggest cold stream),
- The residue of cold stream C3 (1350 kW) is put on a heater,
- Cold stream C9 (entirely below the pinch) is ticked off against the cold side of hot stream H10 (acceptable average DeltaT),
- The residue of hot stream H10 (450 kW) is set side as part of the remaining problem,
- Cold stream C7 is ticked off against hot stream H3;
- The residue of hot stream H3 (950 kW) is put on a cooler.

The data set of the remaining problem is shown in Table 13.2.

Table 13.2

Tsupply	Ttarget	Heat	Shift	U*f	Descript.
°C	°C	kW	K	kW/K,m²	-
180	75	3150	-9	2.00	H1
280	120	2400		0.60	H2
140	45	2850		2.00	H4
170	45	3750		2.00	H7
280	90	2850		1.00	H9
180	165	450		2.00	H10
40	230	3800		1.50	C1
120	260	4900		2.00	C2
50	190	4200		2.00	C4
50	250	4000		2.00	C5
120	210	3150		1.50	C8
60	73	400	-8.0	0.70	C10
325	325	7650		1.00	Heating1
25	40	2650		2.00	Cooling1

The pinch in the remaining problem is caused simultaneously by cold streams C2 and C8, with a very close near pinch from hot stream H4. Processing the original grid with 19 integration bands would generate 94 heat exchanger units. The number of bands can be reduced to 9 as shown in Table 13.3, which then would generate 52 heat exchanger units. The initial network can further be manipulated by allocating shift values to individual streams: shifting cold stream C1 over -10K would reduce the heating load on that stream with 171 kW as shown in Table 13.4. Many initial networks can be developed each of which would lead to alternative final networks.

Table 13.3

Process : Study 10H+10C **Version : Crisscross**

	area	#HEX	AreaCost
Heatit	810.70	16	420.69
Designit	817.59	52	770.48

Descrip.	Heat	U*f	mcp									DeltaTS										
-	kW	kW/m^2,K	kW/K	65.1		135.0		154.3		37.8		32.6		29.1		19.3		35.0		49.7		20.0
				Bands	1		2		3		4		5		6		7		8		9	
Heating1	7650	1.000	76500.0	325.10		325.04		325.00														
H1	3150	2.000	30.0							180.00		171.00		161.00		126.33		105.41		75.00		
H2	2400	0.600	15.0					280.00		189.00		180.00		170.00		137.67		120.00				
H4	2850	2.000	30.0													140.00		114.41		90.89		45.00
H7	3750	2.000	30.0											170.00		137.67		114.41		87.44		45.00
H9	2850	1.000	15.0					280.00		189.00		180.00		170.00		137.67		114.41		90.00		
H10	450	2.000	30.0									180.00		165.00								
C1	3800	1.500	20.0			230.00		172.14		152.64		148.79		142.36		120.00		81.33		40.00		
C2	4900	2.000	35.0	260.00		190.00		172.14		152.64		148.79		138.07		120.00						
C4	4200	2.000	30.0					190.00		152.64		148.79		142.36		120.00		81.33		50.00		
C5	4000	2.000	20.0	250.00		190.00		172.14		152.64		148.79		142.36		120.00		81.33		50.00		
C8	3150	1.500	35.0	210.00		190.00		156.84		152.64		148.79		142.36		120.00						
C10	400	0.700	30.0															73.33		60.00		
Cooling1	2650	2.000	176.7																	40.00		25.00

Table 13.4

Process : Study 10H+10C **Version : Crisscross**

	area	#HEX	AreaCost
Heatit	**902.57**	**17**	**456.72**
Designit	**813.96**	**50**	**755.67**

Descrip.	Heat	U*f	mcp									DeltaTS										
-	kW	kW/m²,K	kW/K	65.1		135.0		154.3		37.8		32.6		29.1		19.3		35.0		49.7		20.0
				Bands	1		2		3		4		5		6		7		8		9	
Heating1	7650	1.000	76500.0	325.10		325.04		325.00														
H1	3150	2.000	30.0							180.00		171.00		161.00		130.33		107.32		75.00		
H2	2400	0.600	15.0					280.00		189.00		180.00		170.00		138.00		120.00				
H4	2850	2.000	30.0													140.00		116.32		88.67		45.00
H7	3750	2.000	30.0											170.00		139.33		116.32		89.67		45.00
H9	2850	1.000	15.0					280.00		189.00		180.00		170.00		139.33		116.32		90.00		
H10	450	2.000	30.0									180.00		165.00								
C1	3800	1.500	20.0			230.00		180.71		161.21		157.36		150.93		130.00		91.33		40.00		
C2	4900	2.000	35.0	260.00		190.00		170.71		151.21		147.36		136.64		120.00						
C4	4200	2.000	30.0					190.00		151.21		147.36		140.93		120.00		81.33		50.00		
C5	4000	2.000	20.0	250.00		190.00		170.71		151.21		147.36		140.93		120.00		81.33		50.00		
C8	3150	1.500	35.0	210.00		190.00		154.18		151.21		147.36		140.93		120.00						
C10	400	0.700	30.0															73.33		60.00		
Cooling1	2650	2.000	176.7																	40.00		25.00

The best results are listed in Table 13.5 and can be compared with networks from literature, only the best networks of which were mentioned. Some networks were finetuned, some of them were revised.

Table 13.5

Published results	Heating	Area	# HEX	# Splits	Energy	Capital	Total
	kW	m^2	-	-	'000 $/y	'000 $/y	'000 $/y
Wu Xiao (2006)	9016.0	3229.00	29 (*)	-	697.90	-	1827.77
Xing Luo et al. (2009)	9513.5	3038.72	26	2	719.58	1033.90	1753.48
Laukkanen et al. (2012)	9500.1	3083.86	24	2	718.50	1021.28	1739.78
Liang et al. (2013) °)	10294.4	2949.56	22	1	782.05	974.82	1756.87
Pavão et al. (2016)	8690.0	3298.97	24	6	653.7	1071.60	1725.30
Yuan Xiao et al. (2018)	9562.9	3149.90	22	0	723.53	1014.53	1738.06
Rathjens and Fieg (2019)	8528.2	3304.24	24	4	640.75	1074.38	1715.13
Zhang et al. (2020)	8798.4	3324.25	22	0	662.37	1063.88	1726.25
Xu et al. (2020)	8881.1	3242.91	24	2	668.99	1056.04	1725.03
Caballero (2021) °)	8469.1	3436.48	23	6	636.03	1098.76	1734.79
Xianli Wu et al. (2021)	9191.2	3276.84	22	0	693.80	1043.73	1737.53
(*) 14 of which multi-stream HEX		°) revised					
This research	9079.0	3256.95	23	2	640.46	1059.49	1699.95
	9082.0	3254.16	23	1	640.67	1059.30	1699.97
	9519.0	3196.53	23	0	671.70	1042.92	1714.62
	9615.0	3194.38	22	1	678.52	1034.38	1712.90
	9591.0	3231.78	22	0	676.81	1040.46	1717.27
	9763.0	3162.94	21	1	739.54	1006.32	1745.86
	9763.0	3180.62	21	0	739.54	1007.93	1747.47

The networks of this study are shown in Figure 13.4 through Figure 13.10.

The network with 23 units and 1 split (Figure 13.5) can be considered as the best with a cost of 1699.97 k$/year; an additional split on hot stream H5 (Figure 13.4) brings a saving of only 23 $/year which would not pay for the additional cost of the split.

The networks with 23 and 22 units belong to one series, the networks with 21 units to another.

Figure 13.1

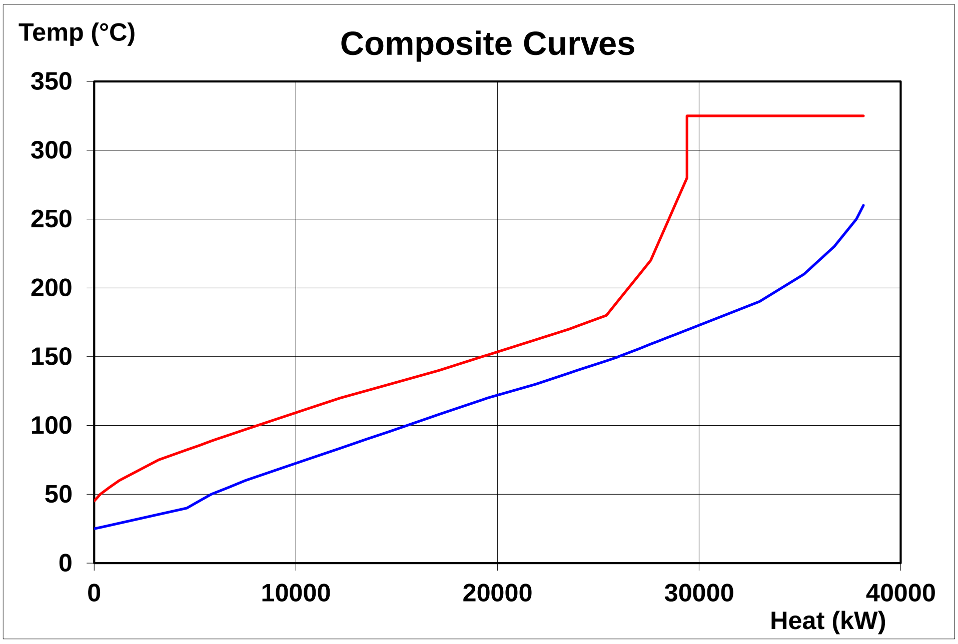


Figure 13.2

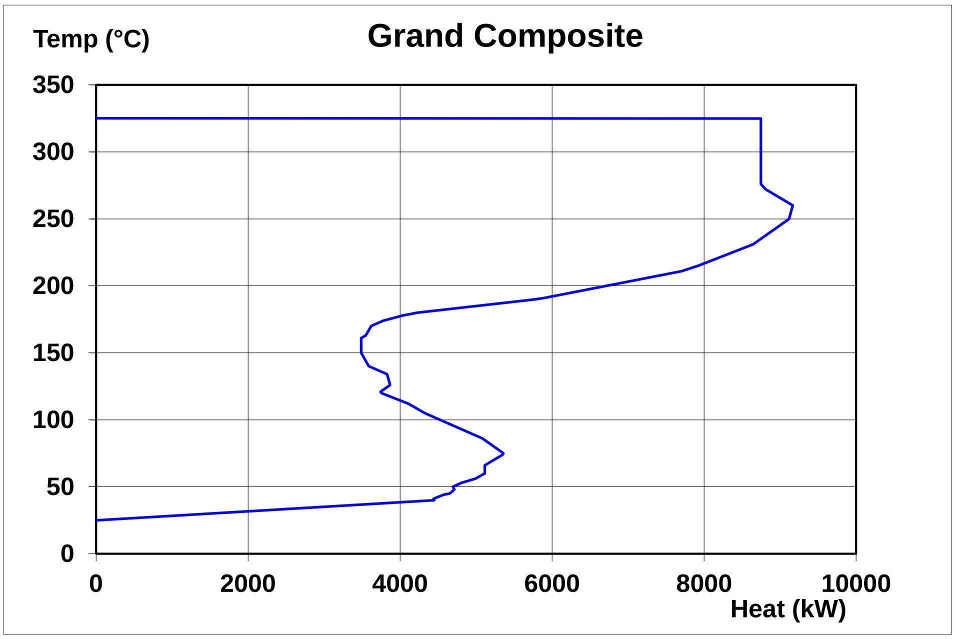


Figure 13.3

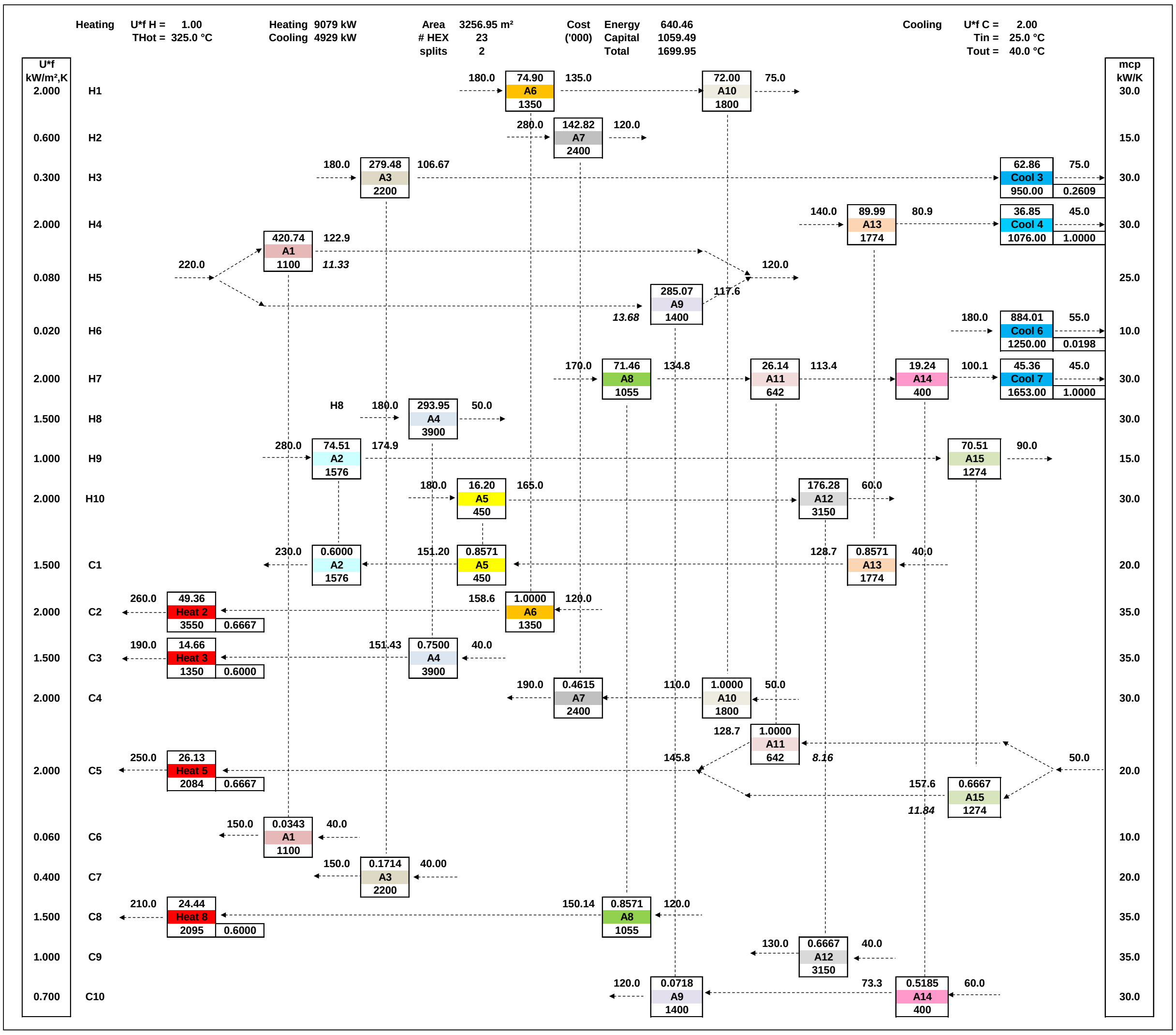

Heating U*f H = 1.00
THot = 325.0 °C
Heating 9079 kW
Cooling 4929 kW
Area 3256.95 m²
HEX 23
splits 2
Cost ('000)
Energy 640.46
Capital 1059.49
Total 1699.95
Cooling U*f C = 2.00
Tin = 25.0 °C
Tout = 40.0 °C
U*f kW/m²,K
mcp kW/K
2.000 H1 30.0
0.600 H2 15.0
0.300 H3 30.0
2.000 H4 30.0
0.080 H5 25.0
0.020 H6 10.0
2.000 H7 30.0
1.500 H8 30.0
1.000 H9 15.0
2.000 H10 30.0
1.500 C1 20.0
2.000 C2 35.0
1.500 C3 35.0
2.000 C4 30.0
2.000 C5 20.0
0.060 C6 10.0
0.400 C7 20.0
1.500 C8 35.0
1.000 C9 35.0
0.700 C10 30.0
180.0 74.90 A6 1350 135.0 72.00 A10 1800 75.0
280.0 142.82 A7 2400 120.0
180.0 279.48 A3 2200 106.67 62.86 Cool 3 950.00 75.0 0.2609
140.0 89.99 A13 1774 80.9 36.85 Cool 4 1076.00 45.0 1.0000
220.0 420.74 A1 1100 122.9 11.33 120.0
285.07 A9 1400 13.68 117.6
180.0 884.01 Cool 6 1250.00 55.0 0.0198
170.0 71.46 A8 1055 134.8 26.14 A11 642 113.4 19.24 A14 400 100.1 45.36 Cool 7 1653.00 45.0 1.0000
H8 180.0 293.95 A4 3900 50.0
280.0 74.51 A2 1576 174.9 70.51 A15 1274 90.0
180.0 16.20 A5 450 165.0 176.28 A12 3150 60.0
230.0 0.6000 A2 1576 151.20 0.8571 A5 450 128.7 0.8571 A13 1774 40.0
260.0 49.36 Heat 2 3550 0.6667 158.6 1.0000 A6 1350 120.0
190.0 14.66 Heat 3 1350 0.6000 151.43 0.7500 A4 3900 40.0
190.0 0.4615 A7 2400 110.0 1.0000 A10 1800 50.0
128.7 1.0000 A11 642 8.16
250.0 26.13 Heat 5 2084 0.6667 145.8 50.0
157.6 0.6667 A15 1274 11.84
150.0 0.0343 A1 1100 40.0
150.0 0.1714 A3 2200 40.00
210.0 24.44 Heat 8 2095 0.6000 150.14 0.8571 A8 1055 120.0
130.0 0.6667 A12 3150 40.0
120.0 0.0718 A9 1400 73.3 0.5185 A14 400 60.0

Figure 13.4

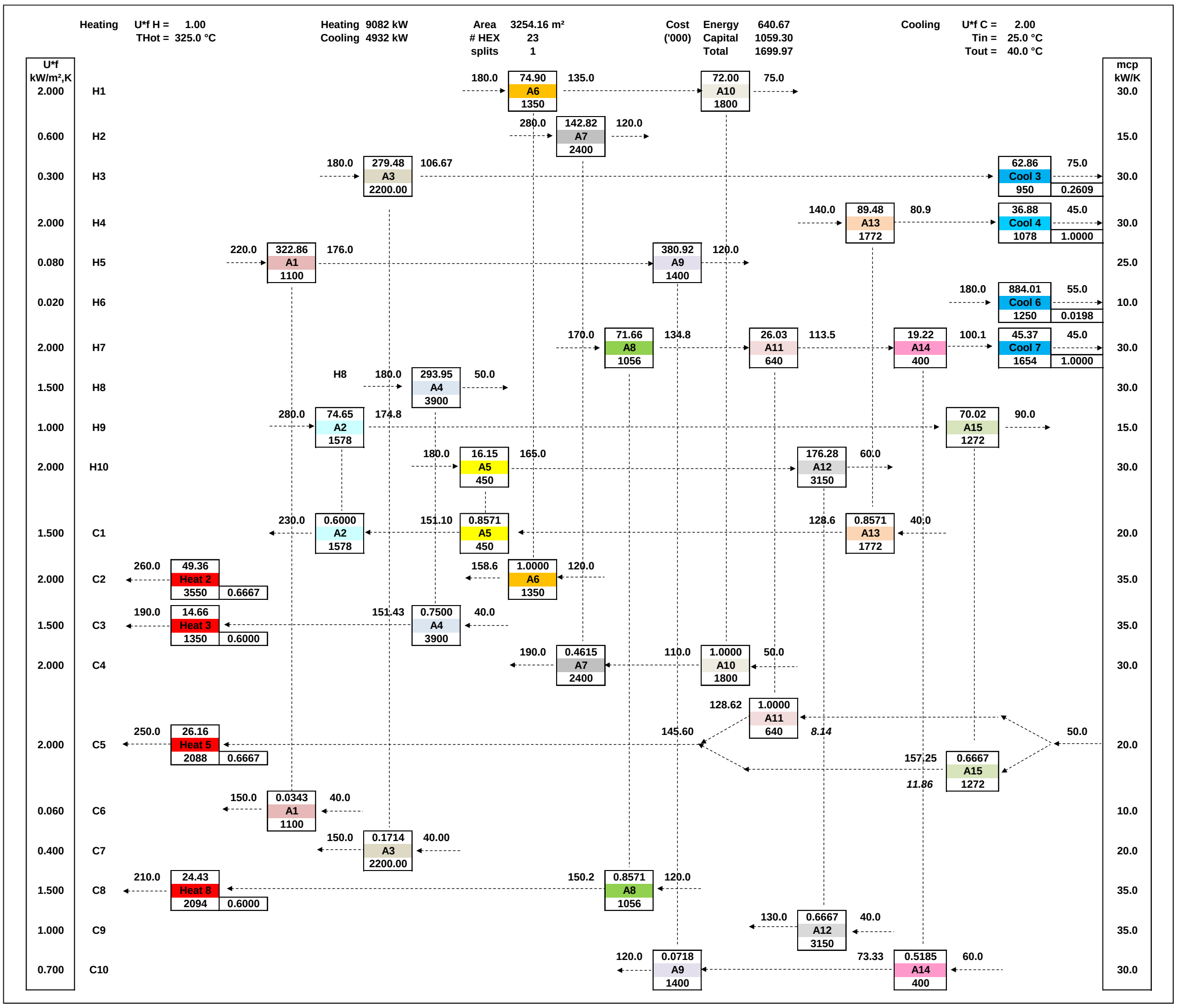

Heating
U*f H = 1.00
THot = 325.0 °C
Heating 9082 kW
Cooling 4932 kW
Area 3254.16 m²
HEX 23
splits 1
Cost ('000)
Energy 640.67
Capital 1059.30
Total 1699.97
Cooling
U*f C = 2.00
Tin = 25.0 °C
Tout = 40.0 °C
U*f kW/m²,K
mcp kW/K
2.000 H1 30.0
0.600 H2 15.0
0.300 H3 30.0
2.000 H4 30.0
0.080 H5 25.0
0.020 H6 10.0
2.000 H7 30.0
1.500 H8 30.0
1.000 H9 15.0
2.000 H10 30.0
1.500 C1 20.0
2.000 C2 35.0
1.500 C3 35.0
2.000 C4 30.0
2.000 C5 20.0
0.060 C6 10.0
0.400 C7 20.0
1.500 C8 35.0
1.000 C9 35.0
0.700 C10 30.0
180.0
74.90 A6 1350
135.0
72.00 A10 1800
75.0
280.0
142.82 A7 2400
120.0
180.0
279.48 A3 2200.00
106.67
62.86 Cool 3 950 0.2609
75.0
140.0
89.48 A13 1772
80.9
36.88 Cool 4 1078 1.0000
45.0
220.0
322.86 A1 1100
176.0
380.92 A9 1400
120.0
180.0
884.01 Cool 6 1250 0.0198
55.0
170.0
71.66 A8 1056
134.8
26.03 A11 640
113.5
19.22 A14 400
100.1
45.37 Cool 7 1654 1.0000
45.0
H8
180.0
293.95 A4 3900
50.0
280.0
74.65 A2 1578
174.8
70.02 A15 1272
90.0
180.0
16.15 A5 450
165.0
176.28 A12 3150
60.0
230.0
0.6000 A2 1578
151.10
0.8571 A5 450
128.6
0.8571 A13 1772
40.0
260.0
49.36 Heat 2 3550 0.6667
158.6
1.0000 A6 1350
120.0
190.0
14.66 Heat 3 1350 0.6000
151.43
0.7500 A4 3900
40.0
190.0
0.4615 A7 2400
110.0
1.0000 A10 1800
50.0
128.62
1.0000 A11 640
145.60
8.14
250.0
26.16 Heat 5 2088 0.6667
157.25
0.6667 A15 1272
11.86
50.0
150.0
0.0343 A1 1100
40.0
150.0
0.1714 A3 2200.00
40.00
210.0
24.43 Heat 8 2094 0.6000
150.2
0.8571 A8 1056
120.0
130.0
0.6667 A12 3150
40.0
120.0
0.0718 A9 1400
73.33
0.5185 A14 400
60.0

Figure 13.5

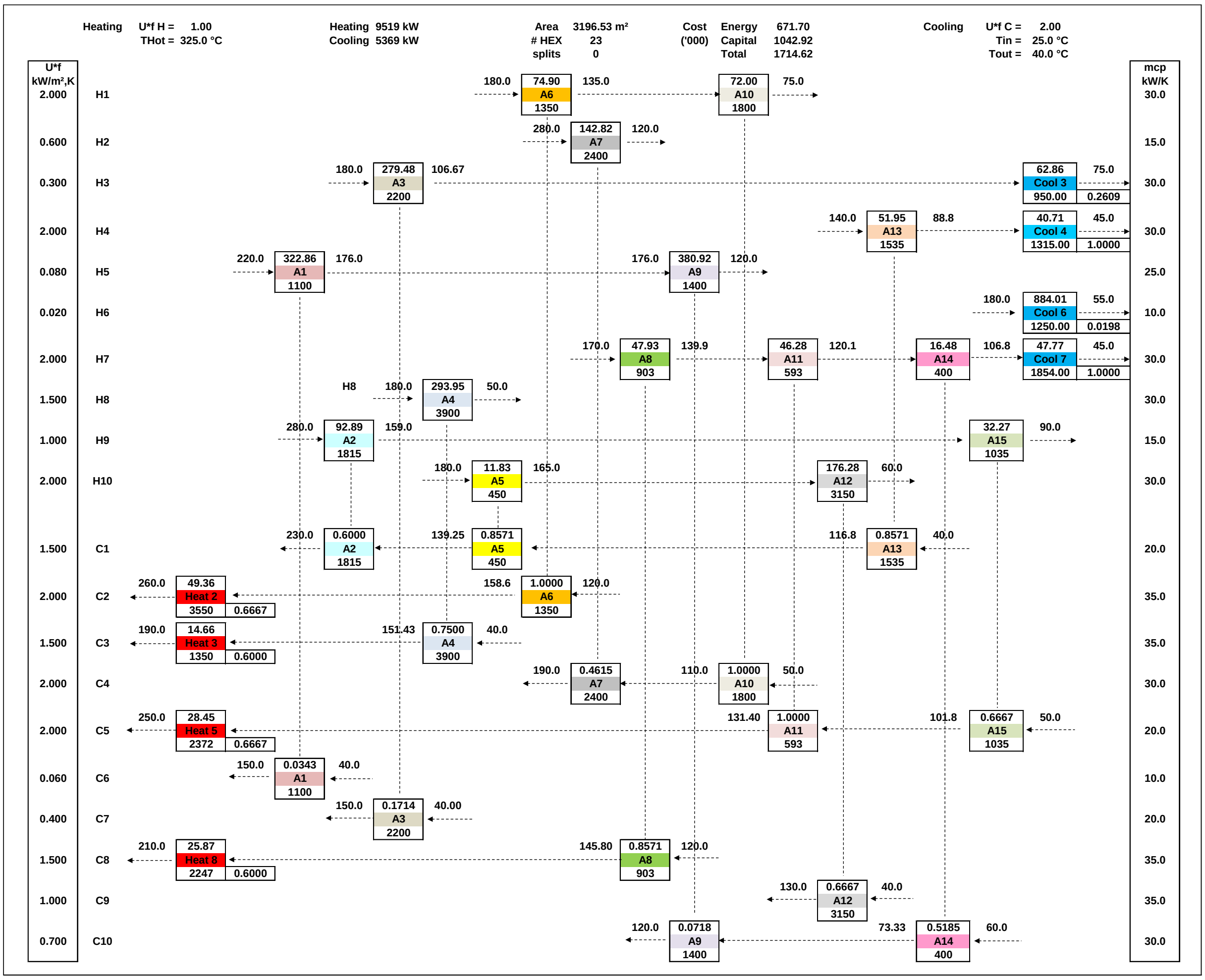

Heating U*f H = 1.00
THot = 325.0 °C
Heating 9519 kW
Cooling 5369 kW
Area 3196.53 m²
HEX 23
splits 0
Cost ('000)
Energy 671.70
Capital 1042.92
Total 1714.62
Cooling U*f C = 2.00
Tin = 25.0 °C
Tout = 40.0 °C
U*f kW/m²,K
mcp kW/K
H1 2.000 30.0
H2 0.600 15.0
H3 0.300 30.0
H4 2.000 30.0
H5 0.080 25.0
H6 0.020 10.0
H7 2.000 30.0
H8 1.500 30.0
H9 1.000 15.0
H10 2.000 30.0
C1 1.500 20.0
C2 2.000 35.0
C3 1.500 35.0
C4 2.000 30.0
C5 2.000 20.0
C6 0.060 10.0
C7 0.400 20.0
C8 1.500 35.0
C9 1.000 35.0
C10 0.700 30.0
180.0 74.90 A6 1350 135.0 72.00 A10 1800 75.0
280.0 142.82 A7 2400 120.0
180.0 279.48 A3 2200 106.67 62.86 Cool 3 950.00 0.2609 75.0
140.0 51.95 A13 1535 88.8 40.71 Cool 4 1315.00 1.0000 45.0
220.0 322.86 A1 1100 176.0 176.0 380.92 A9 1400 120.0
180.0 884.01 Cool 6 1250.00 0.0198 55.0
170.0 47.93 A8 903 139.9 46.28 A11 593 120.1 16.48 A14 400 106.8 47.77 Cool 7 1854.00 1.0000 45.0
H8 180.0 293.95 A4 3900 50.0
280.0 92.89 A2 1815 159.0 32.27 A15 1035 90.0
180.0 11.83 A5 450 165.0 176.28 A12 3150 60.0
230.0 0.6000 A2 1815 139.25 0.8571 A5 450 116.8 0.8571 A13 1535 40.0
260.0 49.36 Heat 2 3550 0.6667 158.6 1.0000 A6 1350 120.0
190.0 14.66 Heat 3 1350 0.6000 151.43 0.7500 A4 3900 40.0
190.0 0.4615 A7 2400 110.0 1.0000 A10 1800 50.0
250.0 28.45 Heat 5 2372 0.6667 131.40 1.0000 A11 593 101.8 0.6667 A15 1035 50.0
150.0 0.0343 A1 1100 40.0
150.0 0.1714 A3 2200 40.00
210.0 25.87 Heat 8 2247 0.6000 145.80 0.8571 A8 903 120.0
130.0 0.6667 A12 3150 40.0
120.0 0.0718 A9 1400 73.33 0.5185 A14 400 60.0

Figure 13.6

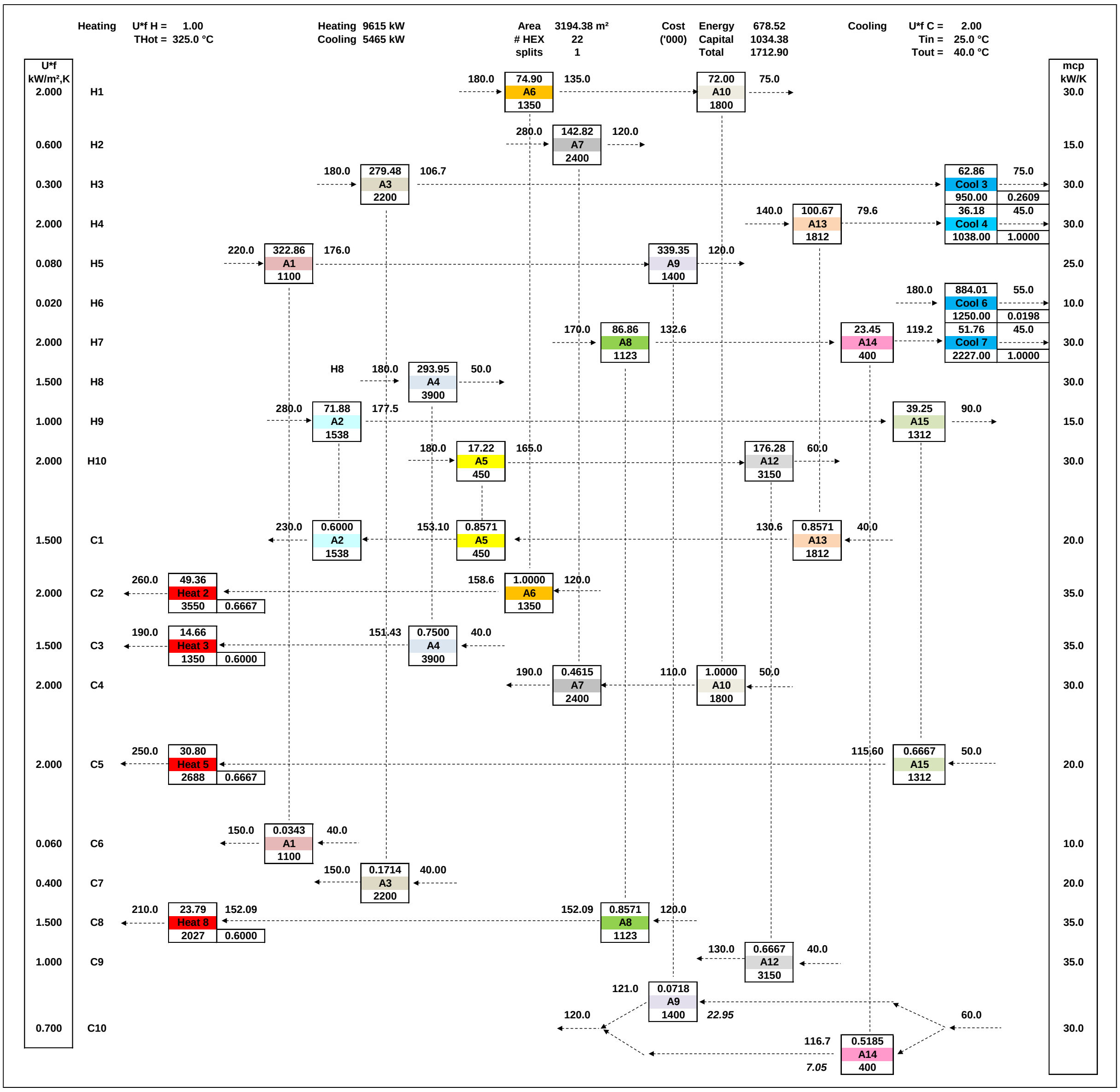

Heating
U*f H = 1.00
THot = 325.0 °C
Heating 9615 kW
Cooling 5465 kW
Area 3194.38 m²
HEX 22
splits 1
Cost ('000)
Energy 678.52
Capital 1034.38
Total 1712.90
Cooling
U*f C = 2.00
Tin = 25.0 °C
Tout = 40.0 °C
U*f kW/m²,K
mcp kW/K
2.000 H1 30.0
180.0 74.90 A6 1350 135.0
72.00 A10 1800 75.0
0.600 H2 15.0
280.0 142.82 A7 2400 120.0
0.300 H3 30.0
180.0 279.48 A3 2200 106.7
62.86 Cool 3 950.00 0.2609 75.0
2.000 H4 30.0
140.0 100.67 A13 1812 79.6
36.18 Cool 4 1038.00 1.0000 45.0
0.080 H5 25.0
220.0 322.86 A1 1100 176.0
339.35 A9 1400 120.0
0.020 H6 10.0
180.0 884.01 Cool 6 1250.00 0.0198 55.0
2.000 H7 30.0
170.0 86.86 A8 1123 132.6
23.45 A14 400 119.2
51.76 Cool 7 2227.00 1.0000 45.0
1.500 H8 30.0
H8 180.0 293.95 A4 3900 50.0
1.000 H9 15.0
280.0 71.88 A2 1538 177.5
39.25 A15 1312 90.0
2.000 H10 30.0
180.0 17.22 A5 450 165.0
176.28 A12 3150 60.0
1.500 C1 20.0
230.0 0.6000 A2 1538
153.10 0.8571 A5 450
130.6 0.8571 A13 1812 40.0
2.000 C2 35.0
260.0 49.36 Heat 2 3550 0.6667
158.6 1.0000 A6 1350 120.0
1.500 C3 35.0
190.0 14.66 Heat 3 1350 0.6000
151.43 0.7500 A4 3900 40.0
2.000 C4 30.0
190.0 0.4615 A7 2400
110.0 1.0000 A10 1800 50.0
2.000 C5 20.0
250.0 30.80 Heat 5 2688 0.6667
115.60 0.6667 A15 1312 50.0
0.060 C6 10.0
150.0 0.0343 A1 1100 40.0
0.400 C7 20.0
150.0 0.1714 A3 2200 40.00
1.500 C8 35.0
210.0 23.79 Heat 8 2027 0.6000 152.09
152.09 0.8571 A8 1123 120.0
1.000 C9 35.0
130.0 0.6667 A12 3150 40.0
0.700 C10 30.0
121.0 0.0718 A9 1400 22.95
120.0
116.7 0.5185 A14 400 7.05
60.0

Figure 13.7

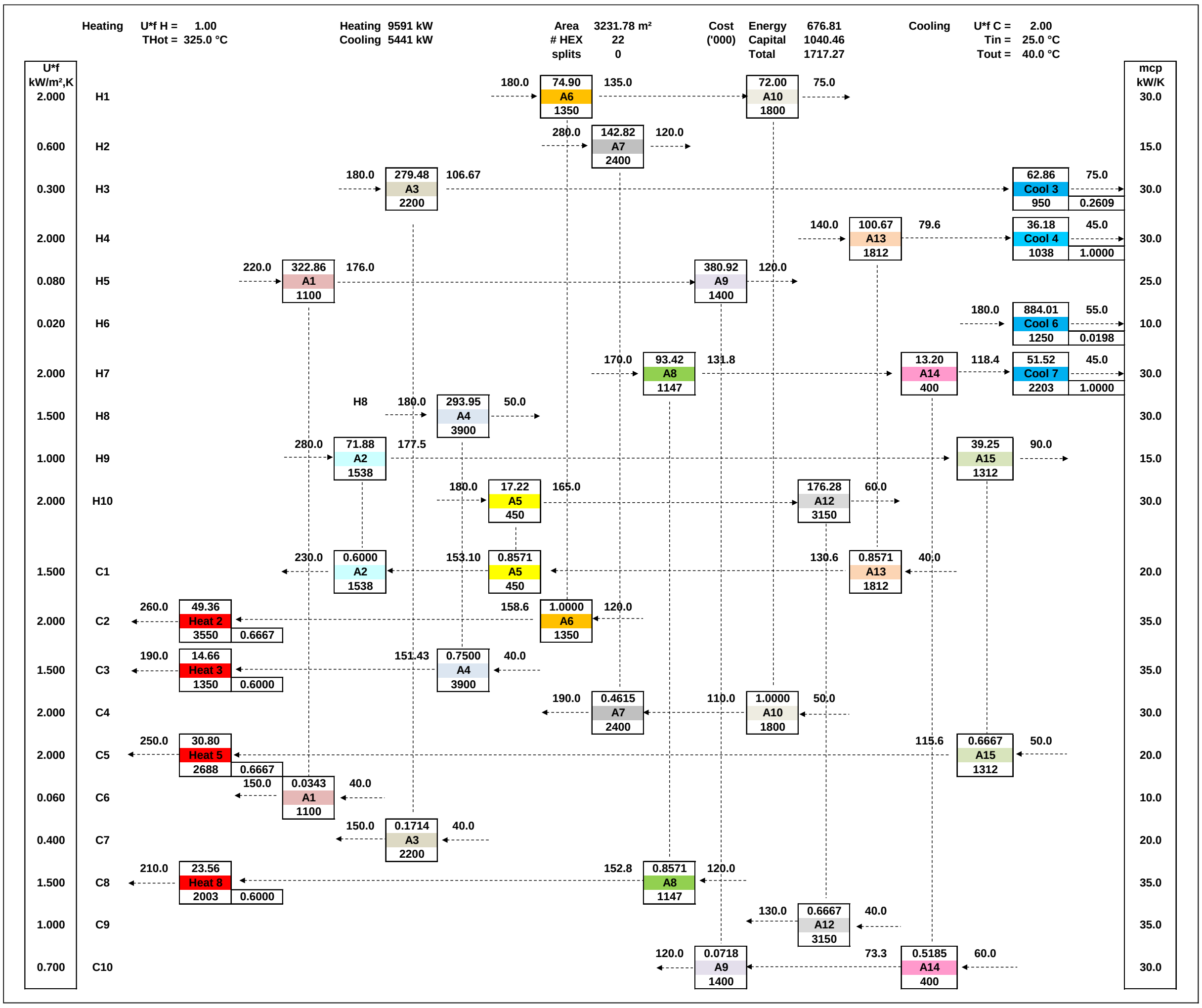

Heating U*f H = 1.00 THot = 325.0 °C
Heating 9591 kW
Cooling 5441 kW
Area 3231.78 m²
HEX 22
splits 0
Cost ('000)
Energy 676.81
Capital 1040.46
Total 1717.27
Cooling U*f C = 2.00 Tin = 25.0 °C Tout = 40.0 °C
U*f kW/m²,K
mcp kW/K
2.000 H1 30.0
0.600 H2 15.0
0.300 H3 30.0
2.000 H4 30.0
0.080 H5 25.0
0.020 H6 10.0
2.000 H7 30.0
1.500 H8 30.0
1.000 H9 15.0
2.000 H10 30.0
1.500 C1 20.0
2.000 C2 35.0
1.500 C3 35.0
2.000 C4 30.0
2.000 C5 20.0
0.060 C6 10.0
0.400 C7 20.0
1.500 C8 35.0
1.000 C9 35.0
0.700 C10 30.0
180.0 74.90 A6 1350 135.0
72.00 A10 1800 75.0
280.0 142.82 A7 2400 120.0
180.0 279.48 A3 2200 106.67
62.86 Cool 3 950 0.2609 75.0
140.0 100.67 A13 1812 79.6
36.18 Cool 4 1038 1.0000 45.0
220.0 322.86 A1 1100 176.0
380.92 A9 1400 120.0
180.0 884.01 Cool 6 1250 0.0198 55.0
170.0 93.42 A8 1147 131.8
13.20 A14 400 118.4
51.52 Cool 7 2203 1.0000 45.0
H8 180.0 293.95 A4 3900 50.0
280.0 71.88 A2 1538 177.5
39.25 A15 1312 90.0
180.0 17.22 A5 450 165.0
176.28 A12 3150 60.0
230.0 0.6000 A2 1538
153.10 0.8571 A5 450
130.6 0.8571 A13 1812 40.0
260.0 49.36 Heat 2 3550 0.6667
158.6 1.0000 A6 1350 120.0
190.0 14.66 Heat 3 1350 0.6000
151.43 0.7500 A4 3900 40.0
190.0 0.4615 A7 2400
110.0 1.0000 A10 1800 50.0
250.0 30.80 Heat 5 2688 0.6667
115.6 0.6667 A15 1312 50.0
150.0 0.0343 A1 1100 40.0
150.0 0.1714 A3 2200 40.0
210.0 23.56 Heat 8 2003 0.6000
152.8 0.8571 A8 1147 120.0
130.0 0.6667 A12 3150 40.0
120.0 0.0718 A9 1400
73.3 0.5185 A14 400 60.0

Figure 13.8

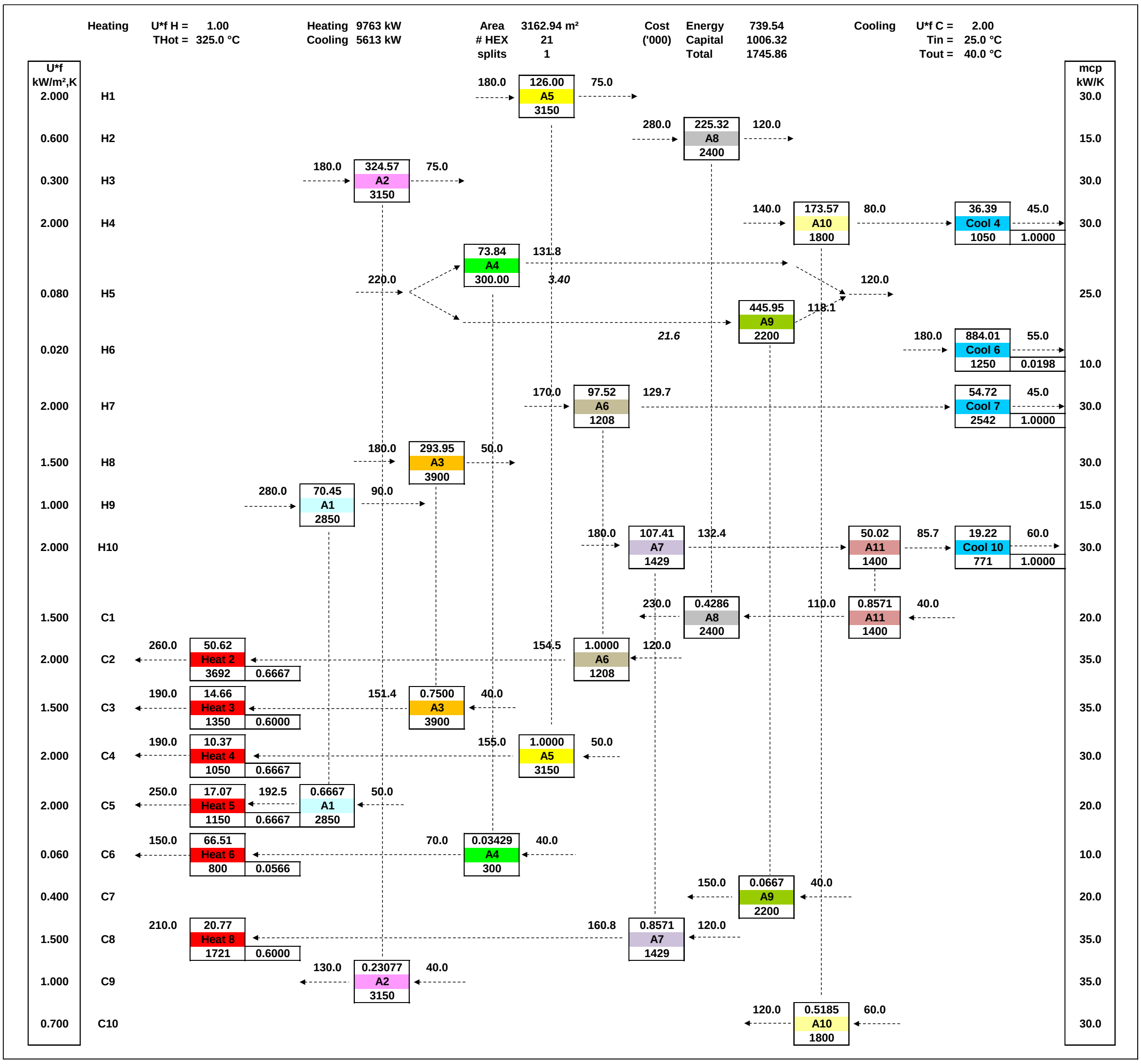

Heating
U*f H = 1.00
THot = 325.0 °C
Heating 9763 kW
Cooling 5613 kW
Area 3162.94 m²
HEX 21
splits 1
Cost ('000)
Energy 739.54
Capital 1006.32
Total 1745.86
Cooling
U*f C = 2.00
Tin = 25.0 °C
Tout = 40.0 °C
U*f kW/m²,K
mcp kW/K
2.000 H1 30.0
0.600 H2 15.0
0.300 H3 30.0
2.000 H4 30.0
0.080 H5 25.0
0.020 H6 10.0
2.000 H7 30.0
1.500 H8 30.0
1.000 H9 15.0
2.000 H10 30.0
1.500 C1 20.0
2.000 C2 35.0
1.500 C3 35.0
2.000 C4 30.0
2.000 C5 20.0
0.060 C6 10.0
0.400 C7 20.0
1.500 C8 35.0
1.000 C9 35.0
0.700 C10 30.0
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 Cool 4 1050 1.0000 45.0
73.84 A4 300.00 131.8
220.0 3.40 120.0
445.95 A9 2200 118.1
21.6
180.0 884.01 Cool 6 1250 0.0198 55.0
170.0 97.52 A6 1208 129.7 54.72 Cool 7 2542 1.0000 45.0
180.0 293.95 A3 3900 50.0
280.0 70.45 A1 2850 90.0
180.0 107.41 A7 1429 132.4 50.02 A11 1400 85.7 19.22 Cool 10 771 1.0000 60.0
230.0 0.4286 A8 2400 110.0 0.8571 A11 1400 40.0
260.0 50.62 Heat 2 3692 0.6667 154.5 1.0000 A6 1208 120.0
190.0 14.66 Heat 3 1350 0.6000 151.4 0.7500 A3 3900 40.0
190.0 10.37 Heat 4 1050 0.6667 155.0 1.0000 A5 3150 50.0
250.0 17.07 Heat 5 1150 0.6667 192.5 0.6667 A1 2850 50.0
150.0 66.51 Heat 6 800 0.0566 70.0 0.03429 A4 300 40.0
150.0 0.0667 A9 2200 40.0
210.0 20.77 Heat 8 1721 0.6000 160.8 0.8571 A7 1429 120.0
130.0 0.23077 A2 3150 40.0
120.0 0.5185 A10 1800 60.0

Figure 13.9

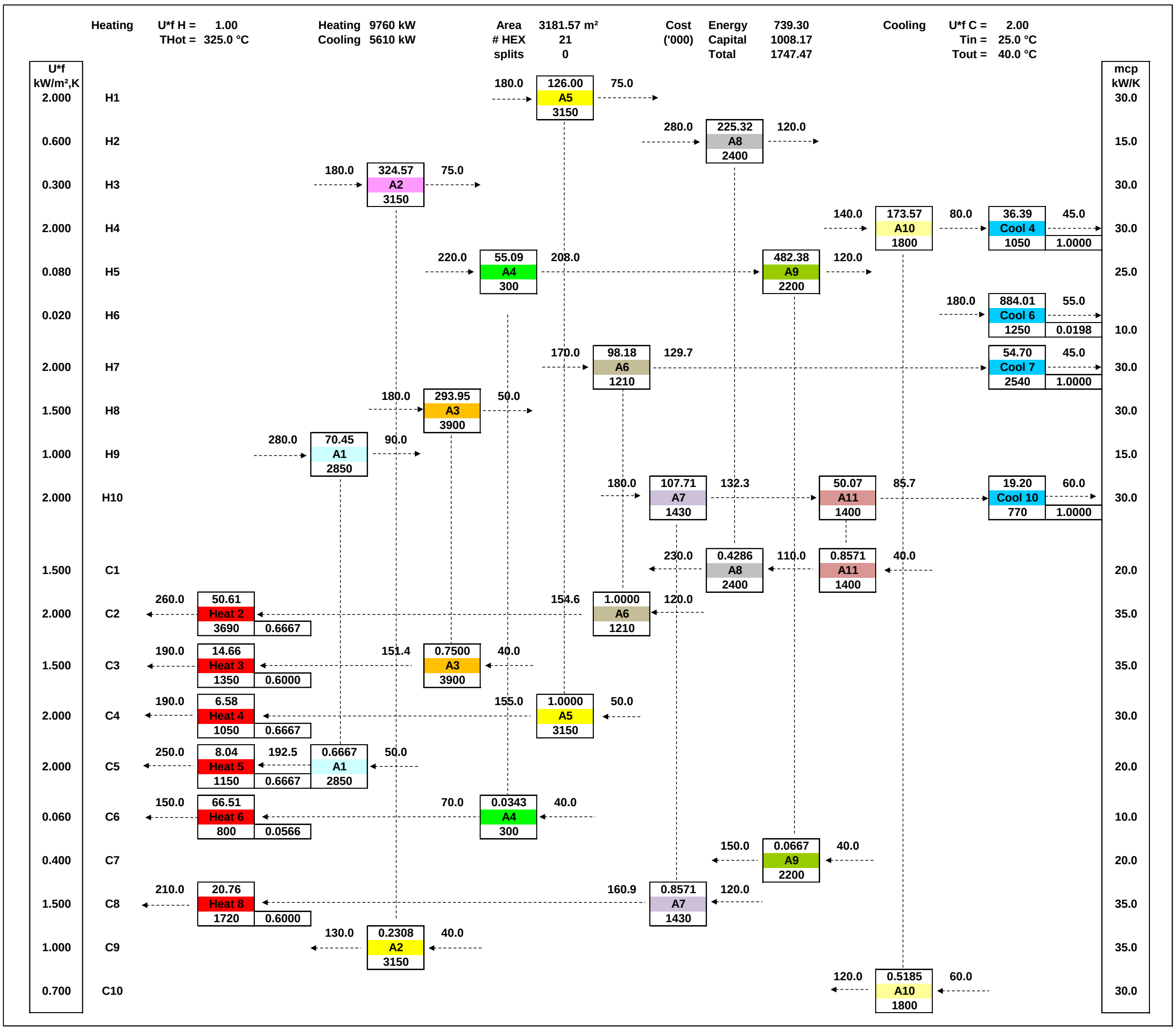

Heating
U*f H = 1.00
THot = 325.0 °C
Heating 9760 kW
Cooling 5610 kW
Area 3181.57 m²
HEX 21
splits 0
Cost ('000)
Energy 739.30
Capital 1008.17
Total 1747.47
Cooling
U*f C = 2.00
Tin = 25.0 °C
Tout = 40.0 °C
U*f kW/m²,K
mcp kW/K
2.000 H1 30.0
0.600 H2 15.0
0.300 H3 30.0
2.000 H4 30.0
0.080 H5 25.0
0.020 H6 10.0
2.000 H7 30.0
1.500 H8 30.0
1.000 H9 15.0
2.000 H10 30.0
1.500 C1 20.0
2.000 C2 35.0
1.500 C3 35.0
2.000 C4 30.0
2.000 C5 20.0
0.060 C6 10.0
0.400 C7 20.0
1.500 C8 35.0
1.000 C9 35.0
0.700 C10 30.0
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 Cool 4 1050 45.0 1.0000
220.0 55.09 A4 300 208.0 482.38 A9 2200 120.0
180.0 884.01 Cool 6 1250 55.0 0.0198
170.0 98.18 A6 1210 129.7 54.70 Cool 7 2540 45.0 1.0000
180.0 293.95 A3 3900 50.0
280.0 70.45 A1 2850 90.0
180.0 107.71 A7 1430 132.3 50.07 A11 1400 85.7 19.20 Cool 10 770 60.0 1.0000
230.0 0.4286 A8 2400 110.0 0.8571 A11 1400 40.0
260.0 50.61 Heat 2 3690 0.6667 154.6 1.0000 A6 1210 120.0
190.0 14.66 Heat 3 1350 0.6000 151.4 0.7500 A3 3900 40.0
190.0 6.58 Heat 4 1050 0.6667 155.0 1.0000 A5 3150 50.0
250.0 8.04 Heat 5 1150 0.6667 192.5 0.6667 A1 2850 50.0
150.0 66.51 Heat 6 800 0.0566 70.0 0.0343 A4 300 40.0
150.0 0.0667 A9 2200 40.0
210.0 20.76 Heat 8 1720 0.6000 160.9 0.8571 A7 1430 120.0
130.0 0.2308 A2 3150 40.0
120.0 0.5185 A10 1800 60.0

Figure 13.10

14 The 20 streams problem from Sorsak and Kravanja (13H7C)

The original data set from Sorsak and Kravanja [68] was adapted by Escobar and Trierweiler [105].

It was further intensively studied by Pavao et al. in 2016 [38] and in 2018 [33], by C Zhang et al. in 2016 [118] and [122], by Xiao et al. in 2017 [101], in 2018 [80] and in 2021 [46], by Z Bao et al. in 2018 [92], by H Zhang et al. in 2018 [115], by Rathjens and Fieg in 2019 [83] and by Xu et al. in 2019 [82]. The data set is shown in Table 14.1.

Table 14.1

Tsupply	Ttarget	Heat	Optimum shift	U*f	Descript.
°C	°C	kW	K	kW/K,m²	-
576.0	437.0	3210.90	3	0.06	H1
599.0	399.0	3044.00	3	0.06	H2
530.0	382.0	2242.20	3	0.06	H3
449.0	237.0	3129.12	3	0.06	H4
368.0	177.0	2043.70	5	0.06	H5
121.0	114.0	1047.20	-36	1.00	H6
202.0	185.0	4389.40	-34	1.00	H7
185.0	113.0	603.36	-37	1.00	H8
140.0	120.0	1197.80	-36	1.00	H9
69.0	66.0	497.37	0	1.00	H10
120.0	68.0	454.48	-36	1.00	H11
67.0	35.0	243.84	0	1.00	H12
1034.5	576.0	9766.05	0	0.06	H13
123.0	343.0	2334.20	49	0.06	C1
20.0	156.0	904.40	0	1.20	C2
156.0	157.0	3291.00	-3	2.00	C3
20.0	182.0	4314.06	0	1.20	C4
182.0	318.0	4241.84	1	1.20	C5
318.0	320.0	8023.66	-3	2.00	C6
322.0	923.8	10591.33	49	0.06	C7
927	927	1831.07	-46	5.00	Heating
9	17	0.00		1.00	Cooling

Cost data

Heating: 250 \$/kW,year Cooling: 25 \$/kW,year

HEX cost: 4000 + 500 x Area $^{0.83}$ \$/year

Shift values in Table 14.1 were set with Crisscross Optimisation for minimum area.

Composite curves are shown in Figure 14.1 for classic pinch analysis. Available driving force is low at lower temperatures but is much higher with Crisscross as illustrated in the DeltaT versus Q diagram in Figure 14.2.

Trade-off between energy and capital indicates that no cooling is required. Total cost as a function of heating is shown in Figure 14.3 where results both from classic analysis and after Crisscross Optimisation are presented. The target with Crisscross is a cost of 1428.42 k\$/year for 20 units and a heat exchanger area of 4467.63 m²; this is 4% lower than the target in the classic approach.

The design procedure started with pinch analysis with crisscross optimiation, generation of the grid, application of a tick-off procedure, study of potential splits and swaps to eliminate loops.

An intermediate near-to-optimum network with a cost of 1403.99 k$/year is shown in Figure 14.4. A loop can be identified, which can be broken by swapping the cold sides of heat exchanger units A17 and A18. The result is a network with a cost of 1397.91 k$/year which is the optimum network with 20 units without splits. That network is also the basis for the optimum networks with splits. The networks with twenty units and one heater on cold stream C7 are mentioned in Table 14.2.

Then a new heuristic rule was applied: “check whether the introduction of an additional utility unit creates a loop through which further optimisation is possible”. This rule was applied on cold stream C1, creating a loop between heaters Heat 1 and Heat 7, leading to another near-to-optimum network with 21 units and a cost of 1391.97 k$/year as shown in Figure 14.5. Introducing splits and optimisation via the loop generates optimum networks with 21 units and with 1 and 2 splits. The same heuristic rule was also applied on cold stream C5, creating a loop between heaters Heat 5 and Heat 7 as shown in Figure 14.6. Optimisation within the loop leads to the elimination of heat exchanger A2 and an optimum network with 21 units without splits.

The best networks with 21 and 20 units are reported in Tabel 14.2, where they can be compared with the results of published networks. They are shown in Figures 14.7 through 14.12. The costs of the best networks are below target which was 1428.42 k$/year. These costs are up to 2.0% lower than the best network published so far [46]; more than 30 networks could be developed with lower cost.

Crisscross optimisation prior to design combined with appropriate heuristics appears to be a powerful tool for synthesising optimum networks.

Table 14.2

Published studies	Heating	Area	Units	Splits	Cost	Heaters
	kW	m^2	#	#	'000 $/year	on stream
Escobar and Trierweiler (2013) *	1938.00	5551.08	21	5	1537.09	C7
Reoptimised by Pavao (2016)	1938.00	5389.05	21	5	1516.48	C7
Developed and optimised in this study	1938.00	5300.94	20	5	1489.67	C7
C. Zhang et al. (2016)	1831.07	5969.00	23	0	1536.99	H13,C1, C4, C5, C6
Pavao (2018)**	2074.91	5038.59	22	5	1467.80	C1, C4, C7
Bao et al (2018)	2077.51	5053.20	22	3	1462.32	C1, C4, C5, C6
Xiao, Cui, Sun, Chen (2018)	1867.57	5316.06	21	0	1424.17	C1, C4, C5, C6, C7
Hongliang Zhang and Cui (2018)	1831.07	5110.00	22	0	1418.98	C1, C5, C6
Xu et al. (2019) [14]	1831.07	5295.85	20	0	1412.80	C1, C5, C6
Rathjens and Fieg (2019)	1831.07	5142.15	20	4	1407.20	C1, C2, C6
Xiao, Kayange et al. (2021) **	1831.07	5025.08	21	0	1396.49	C1, C5, C6
This study	1831.07	4685.85	21	2	1368.99	C1, C7
	1831.07	4784.79	21	1	1369.07	C1, C7
	1831.07	4689.02	21	0	1389.26	C1, C5, C7
	1831.07	4784.32	20	2	1372.97	C7
	1831.07	4784.79	20	1	1373.04	C7
	1831.07	5055.57	20	0	1397.91	C7
* Revised by Pavao (2016) [7]						
** Revised by the author						
Networks with a heating load of 1831.07 kW need no coolers						

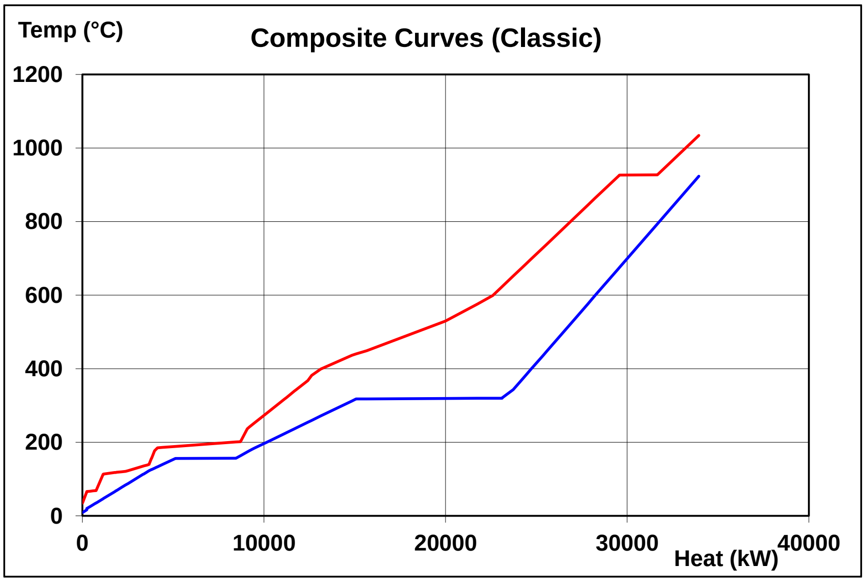


Figure 14.1

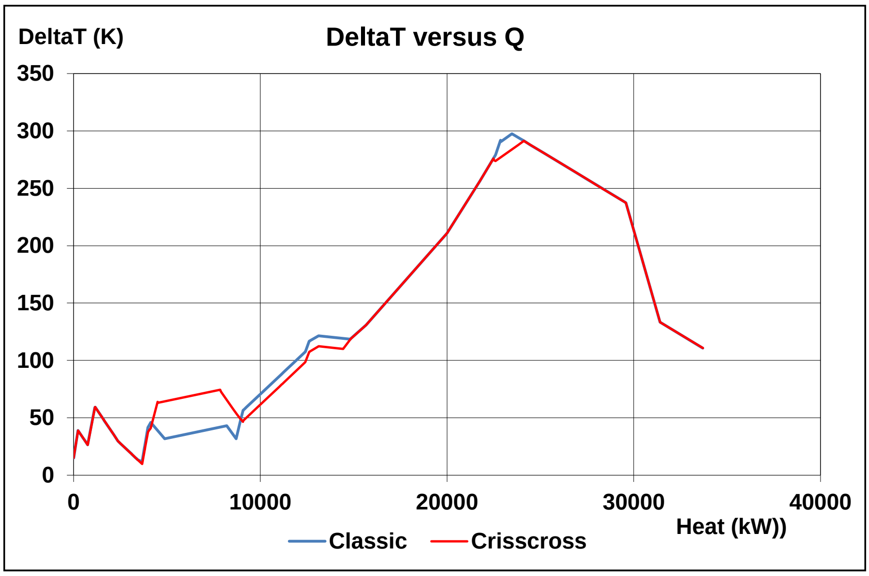


Figure 14.2

Figure 14.3

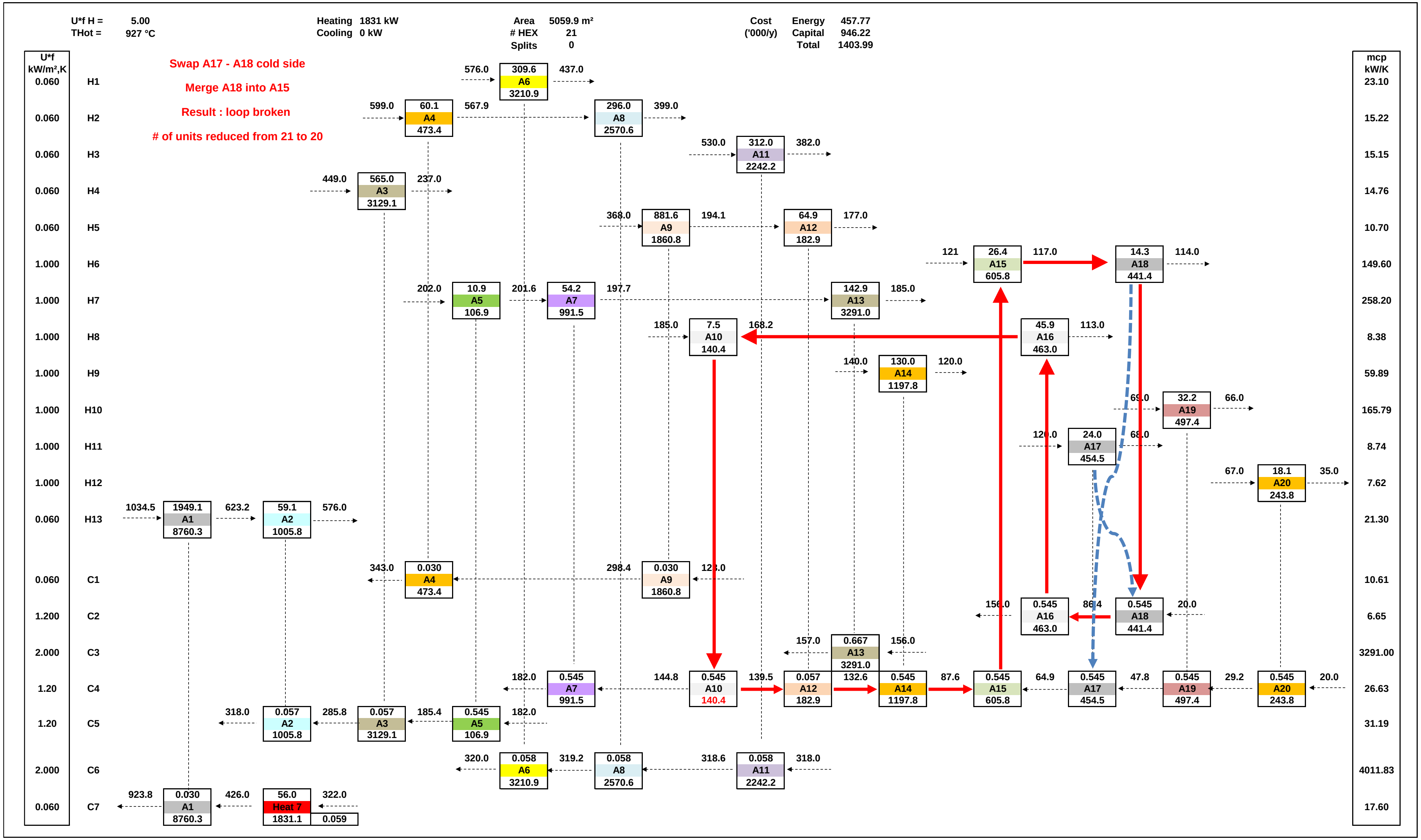

U*f H = 5.00
THot = 927 °C
Heating 1831 kW
Cooling 0 kW
Area 5059.9 m²
HEX 21
Splits 0
Cost ('000/y)
Energy 457.77
Capital 946.22
Total 1403.99
U*f kW/m²,K
mcp kW/K
Swap A17 - A18 cold side
Merge A18 into A15
Result : loop broken
# of units reduced from 21 to 20
0.060 H1 23.10
576.0 309.6 A6 3210.9 437.0
0.060 H2 15.22
599.0 60.1 A4 473.4 567.9 296.0 A8 2570.6 399.0
0.060 H3 15.15
530.0 312.0 A11 2242.2 382.0
0.060 H4 14.76
449.0 565.0 A3 3129.1 237.0
0.060 H5 10.70
368.0 881.6 A9 1860.8 194.1 64.9 A12 182.9 177.0
1.000 H6 149.60
121 26.4 A15 605.8 117.0 14.3 A18 441.4 114.0
1.000 H7 258.20
202.0 10.9 A5 106.9 201.6 54.2 A7 991.5 197.7 142.9 A13 3291.0 185.0
1.000 H8 8.38
185.0 7.5 A10 140.4 168.2 45.9 A16 463.0 113.0
1.000 H9 59.89
140.0 130.0 A14 1197.8 120.0
1.000 H10 165.79
69.0 32.2 A19 497.4 66.0
1.000 H11 8.74
120.0 24.0 A17 454.5 68.0
1.000 H12 7.62
67.0 18.1 A20 243.8 35.0
0.060 H13 21.30
1034.5 1949.1 A1 8760.3 623.2 59.1 A2 1005.8 576.0
0.060 C1 10.61
343.0 0.030 A4 473.4 298.4 0.030 A9 1860.8 123.0
1.200 C2 6.65
156.0 0.545 A16 463.0 86.4 0.545 A18 441.4 20.0
2.000 C3 3291.00
157.0 0.667 A13 3291.0 156.0
1.20 C4 26.63
182.0 0.545 A7 991.5 144.8 0.545 A10 140.4 139.5 0.057 A12 182.9 132.6 0.545 A14 1197.8 87.6 0.545 A15 605.8 64.9 0.545 A17 454.5 47.8 0.545 A19 497.4 29.2 0.545 A20 243.8 20.0
1.20 C5 31.19
318.0 0.057 A2 1005.8 285.8 0.057 A3 3129.1 185.4 0.545 A5 106.9 182.0
2.000 C6 4011.83
320.0 0.058 A6 3210.9 319.2 0.058 A8 2570.6 318.6 0.058 A11 2242.2 318.0
0.060 C7 17.60
923.8 0.030 A1 8760.3 426.0 56.0 Heat 7 1831.1 322.0 0.059

Figure 14.4

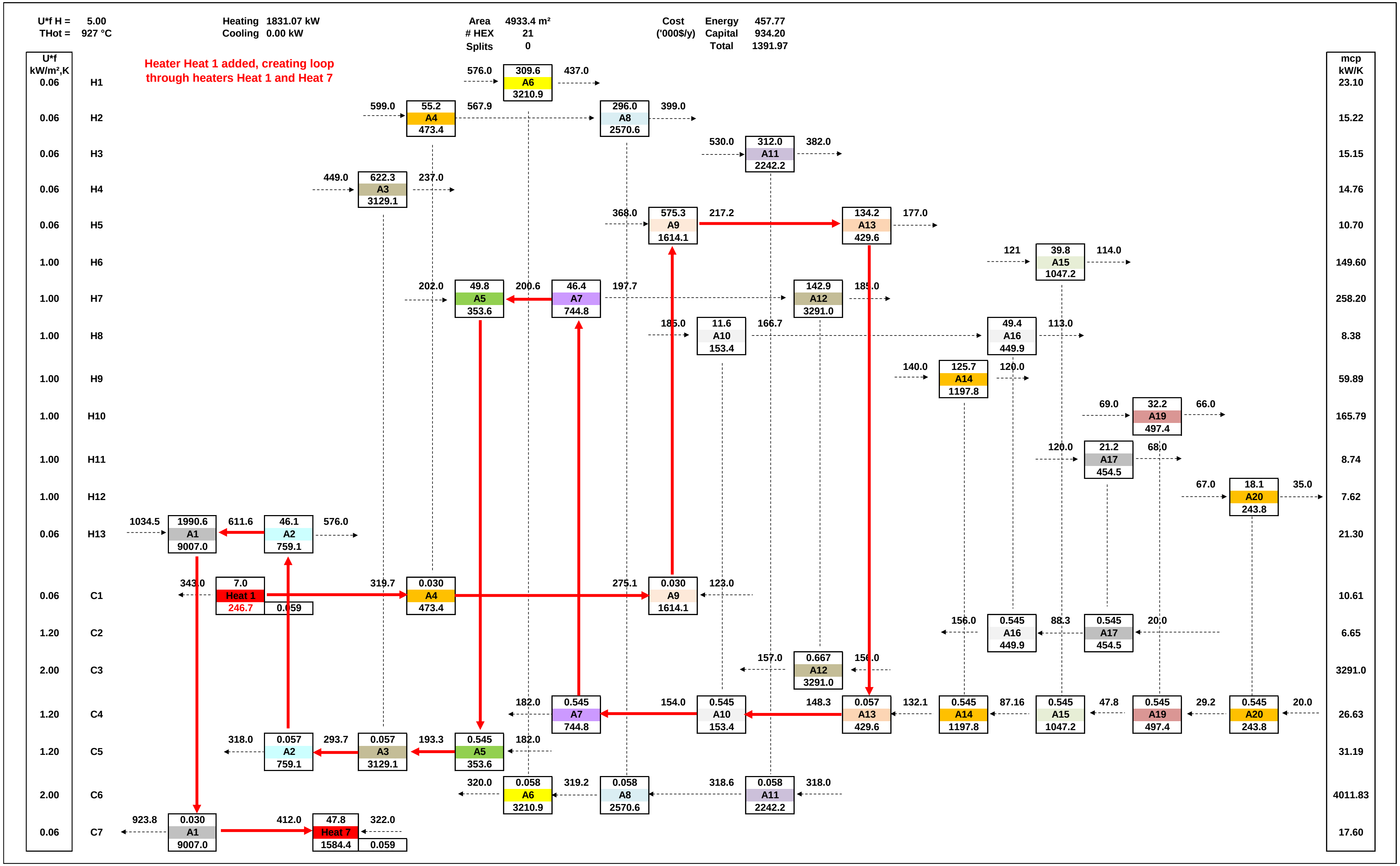

U*f H = 5.00
THot = 927 °C
Heating 1831.07 kW
Cooling 0.00 kW
Area 4933.4 m²
HEX 21
Splits 0
Cost ('000$/y)
Energy 457.77
Capital 934.20
Total 1391.97
Heater Heat 1 added, creating loop through heaters Heat 1 and Heat 7
U*f kW/m²,K
mcp kW/K
0.06 H1 23.10
0.06 H2 15.22
0.06 H3 15.15
0.06 H4 14.76
0.06 H5 10.70
1.00 H6 149.60
1.00 H7 258.20
1.00 H8 8.38
1.00 H9 59.89
1.00 H10 165.79
1.00 H11 8.74
1.00 H12 7.62
0.06 H13 21.30
0.06 C1 10.61
1.20 C2 6.65
2.00 C3 3291.0
1.20 C4 26.63
1.20 C5 31.19
2.00 C6 4011.83
0.06 C7 17.60
576.0 309.6 A6 3210.9 437.0
599.0 55.2 A4 473.4 567.9 296.0 A8 2570.6 399.0
530.0 312.0 A11 2242.2 382.0
449.0 622.3 A3 3129.1 237.0
368.0 575.3 A9 1614.1 217.2 134.2 A13 429.6 177.0
121 39.8 A15 1047.2 114.0
202.0 49.8 A5 353.6 200.6 46.4 A7 744.8 197.7 142.9 A12 3291.0 185.0
185.0 11.6 A10 153.4 166.7 49.4 A16 449.9 113.0
140.0 125.7 A14 1197.8 120.0
69.0 32.2 A19 497.4 66.0
120.0 21.2 A17 454.5 68.0
67.0 18.1 A20 243.8 35.0
1034.5 1990.6 A1 9007.0 611.6 46.1 A2 759.1 576.0
343.0 7.0 Heat 1 246.7 0.059 319.7 0.030 A4 473.4 275.1 0.030 A9 1614.1 123.0
156.0 0.545 A16 449.9 88.3 0.545 A17 454.5 20.0
157.0 0.667 A12 3291.0 156.0
182.0 0.545 A7 744.8 154.0 0.545 A10 153.4 148.3 0.057 A13 429.6 132.1 0.545 A14 1197.8 87.16 0.545 A15 1047.2 47.8 0.545 A19 497.4 29.2 0.545 A20 243.8 20.0
318.0 0.057 A2 759.1 293.7 0.057 A3 3129.1 193.3 0.545 A5 353.6 182.0
320.0 0.058 A6 3210.9 319.2 0.058 A8 2570.6 318.6 0.058 A11 2242.2 318.0
923.8 0.030 A1 9007.0 412.0 47.8 Heat 7 1584.4 0.059 322.0

Figure 14.5

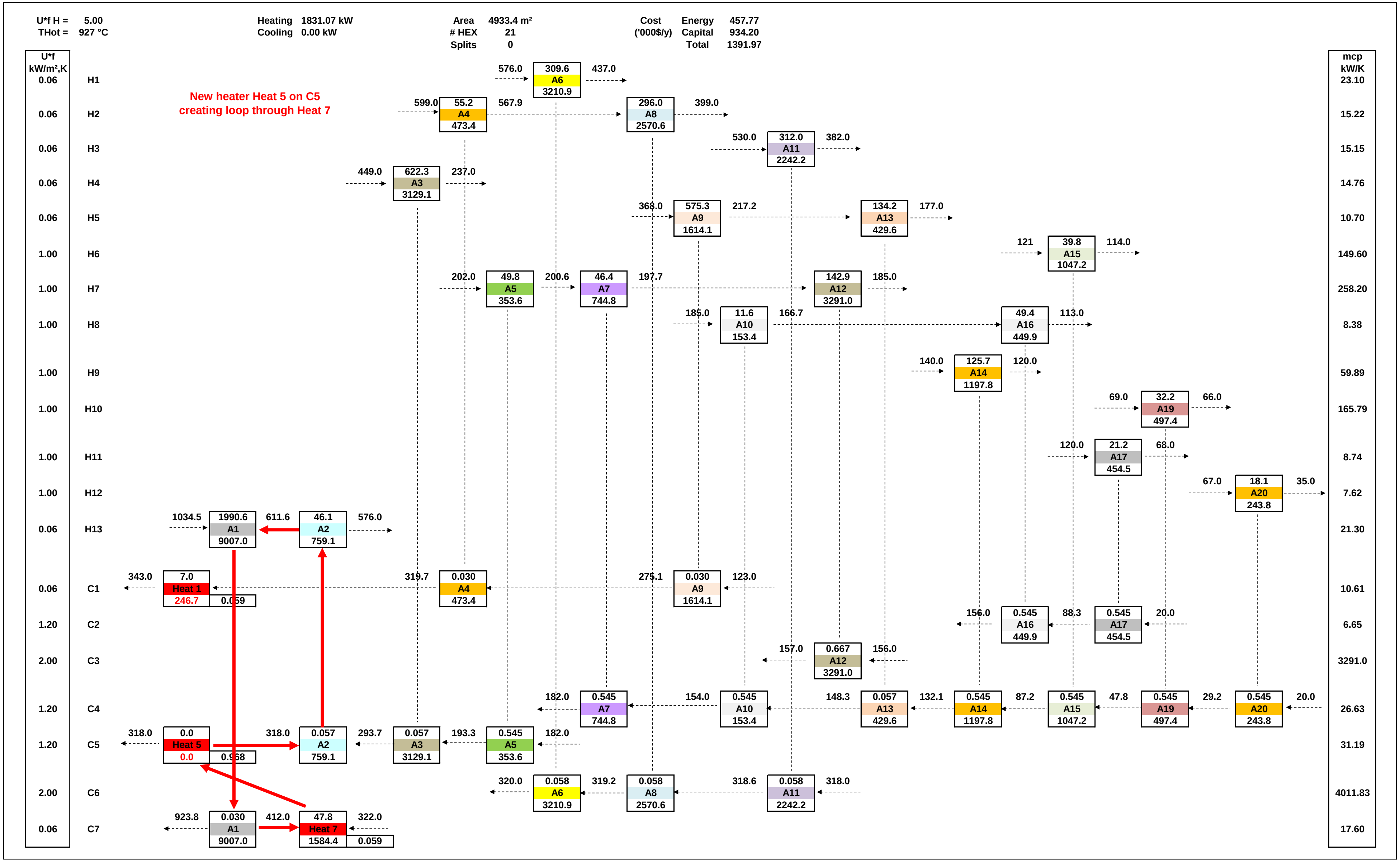

U*f H = 5.00
THot = 927 °C
Heating 1831.07 kW
Cooling 0.00 kW
Area 4933.4 m²
HEX 21
Splits 0
Cost ('000$/y)
Energy 457.77
Capital 934.20
Total 1391.97
U*f kW/m²,K
mcp kW/K
New heater Heat 5 on C5 creating loop through Heat 7
H1 0.06 23.10
H2 0.06 15.22
H3 0.06 15.15
H4 0.06 14.76
H5 0.06 10.70
H6 1.00 149.60
H7 1.00 258.20
H8 1.00 8.38
H9 1.00 59.89
H10 1.00 165.79
H11 1.00 8.74
H12 1.00 7.62
H13 0.06 21.30
C1 0.06 10.61
C2 1.20 6.65
C3 2.00 3291.0
C4 1.20 26.63
C5 1.20 31.19
C6 2.00 4011.83
C7 0.06 17.60
576.0 309.6 A6 3210.9 437.0
599.0 55.2 A4 473.4 567.9 296.0 A8 2570.6 399.0
530.0 312.0 A11 2242.2 382.0
449.0 622.3 A3 3129.1 237.0
368.0 575.3 A9 1614.1 217.2 134.2 A13 429.6 177.0
121 39.8 A15 1047.2 114.0
202.0 49.8 A5 353.6 200.6 46.4 A7 744.8 197.7 142.9 A12 3291.0 185.0
185.0 11.6 A10 153.4 166.7 49.4 A16 449.9 113.0
140.0 125.7 A14 1197.8 120.0
69.0 32.2 A19 497.4 66.0
120.0 21.2 A17 454.5 68.0
67.0 18.1 A20 243.8 35.0
1034.5 1990.6 A1 9007.0 611.6 46.1 A2 759.1 576.0
343.0 7.0 Heat 1 246.7 0.059 319.7 0.030 A4 473.4 275.1 0.030 A9 1614.1 123.0
156.0 0.545 A16 449.9 88.3 0.545 A17 454.5 20.0
157.0 0.667 A12 3291.0 156.0
182.0 0.545 A7 744.8 154.0 0.545 A10 153.4 148.3 0.057 A13 429.6 132.1 0.545 A14 1197.8 87.2 0.545 A15 1047.2 47.8 0.545 A19 497.4 29.2 0.545 A20 243.8 20.0
318.0 0.0 Heat 5 0.0 0.968 318.0 0.057 A2 759.1 293.7 0.057 A3 3129.1 193.3 0.545 A5 353.6 182.0
320.0 0.058 A6 3210.9 319.2 0.058 A8 2570.6 318.6 0.058 A11 2242.2 318.0
923.8 0.030 A1 9007.0 412.0 47.8 Heat 7 1584.4 0.059 322.0

Figure 14.6

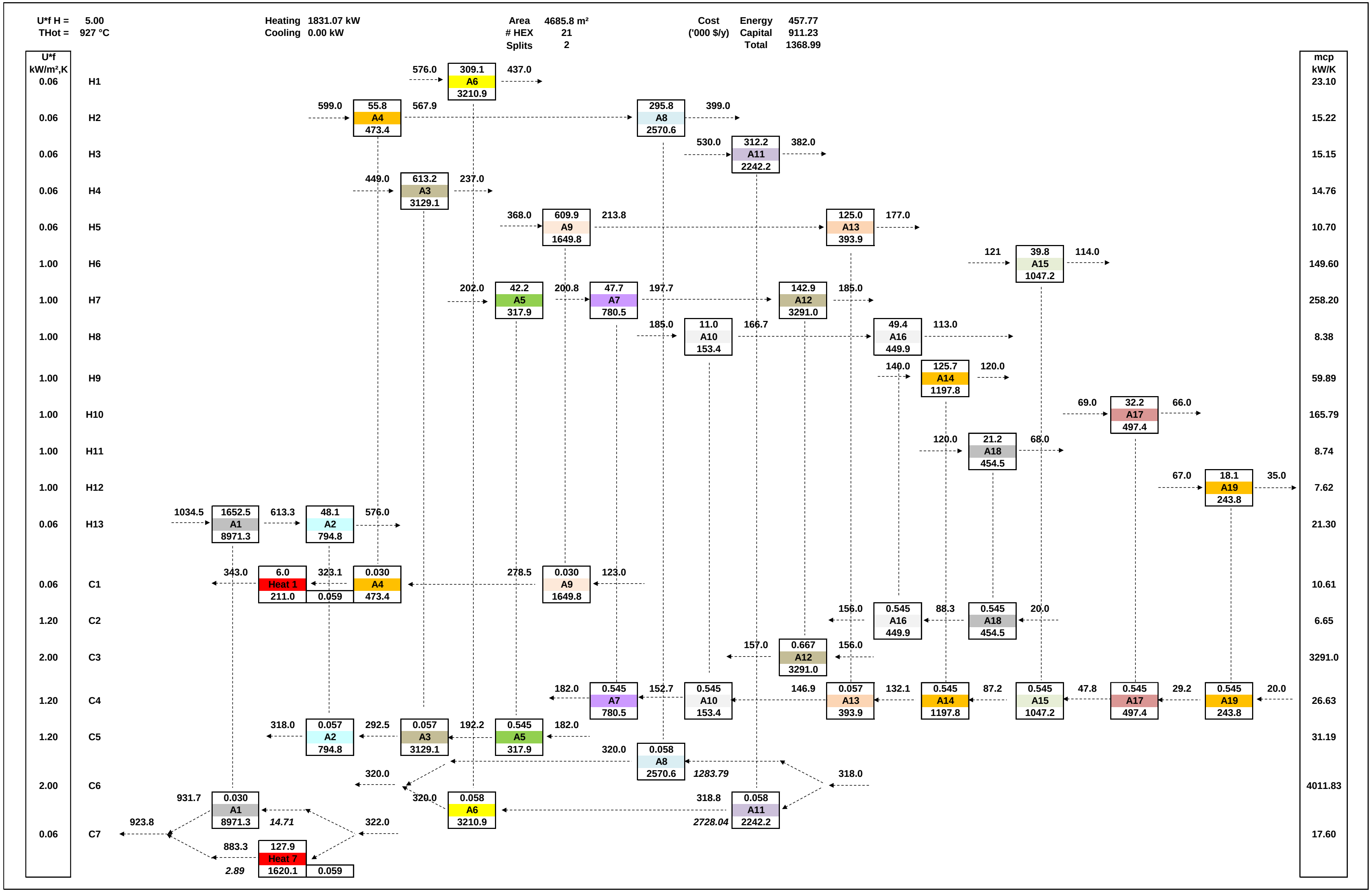

U*f H = 5.00
THot = 927 °C
Heating 1831.07 kW
Cooling 0.00 kW
Area 4685.8 m²
HEX 21
Splits 2
Cost ('000 $/y)
Energy 457.77
Capital 911.23
Total 1368.99
U*f kW/m²,K
mcp kW/K
0.06 H1 23.10
0.06 H2 15.22
0.06 H3 15.15
0.06 H4 14.76
0.06 H5 10.70
1.00 H6 149.60
1.00 H7 258.20
1.00 H8 8.38
1.00 H9 59.89
1.00 H10 165.79
1.00 H11 8.74
1.00 H12 7.62
0.06 H13 21.30
0.06 C1 10.61
1.20 C2 6.65
2.00 C3 3291.0
1.20 C4 26.63
1.20 C5 31.19
2.00 C6 4011.83
0.06 C7 17.60
576.0 309.1 A6 3210.9 437.0
599.0 55.8 A4 473.4 567.9 295.8 A8 2570.6 399.0
530.0 312.2 A11 2242.2 382.0
449.0 613.2 A3 3129.1 237.0
368.0 609.9 A9 1649.8 213.8 125.0 A13 393.9 177.0
121 39.8 A15 1047.2 114.0
202.0 42.2 A5 317.9 200.8 47.7 A7 780.5 197.7 142.9 A12 3291.0 185.0
185.0 11.0 A10 153.4 166.7 49.4 A16 449.9 113.0
140.0 125.7 A14 1197.8 120.0
69.0 32.2 A17 497.4 66.0
120.0 21.2 A18 454.5 68.0
67.0 18.1 A19 243.8 35.0
1034.5 1652.5 A1 8971.3 613.3 48.1 A2 794.8 576.0
343.0 6.0 Heat 1 211.0 323.1 0.059 0.030 A4 473.4 278.5 0.030 A9 1649.8 123.0
156.0 0.545 A16 449.9 88.3 0.545 A18 454.5 20.0
157.0 0.667 A12 3291.0 156.0
182.0 0.545 A7 780.5 152.7 0.545 A10 153.4 146.9 0.057 A13 393.9 132.1 0.545 A14 1197.8 87.2 0.545 A15 1047.2 47.8 0.545 A17 497.4 29.2 0.545 A19 243.8 20.0
318.0 0.057 A2 794.8 292.5 0.057 A3 3129.1 192.2 0.545 A5 317.9 182.0
320.0 0.058 A8 2570.6 1283.79 318.0
320.0 320.0 0.058 A6 3210.9 318.8 0.058 A11 2242.2 2728.04
931.7 0.030 A1 8971.3 14.71 322.0
923.8
883.3 127.9 Heat 7 1620.1 0.059
2.89

Figure 14.7

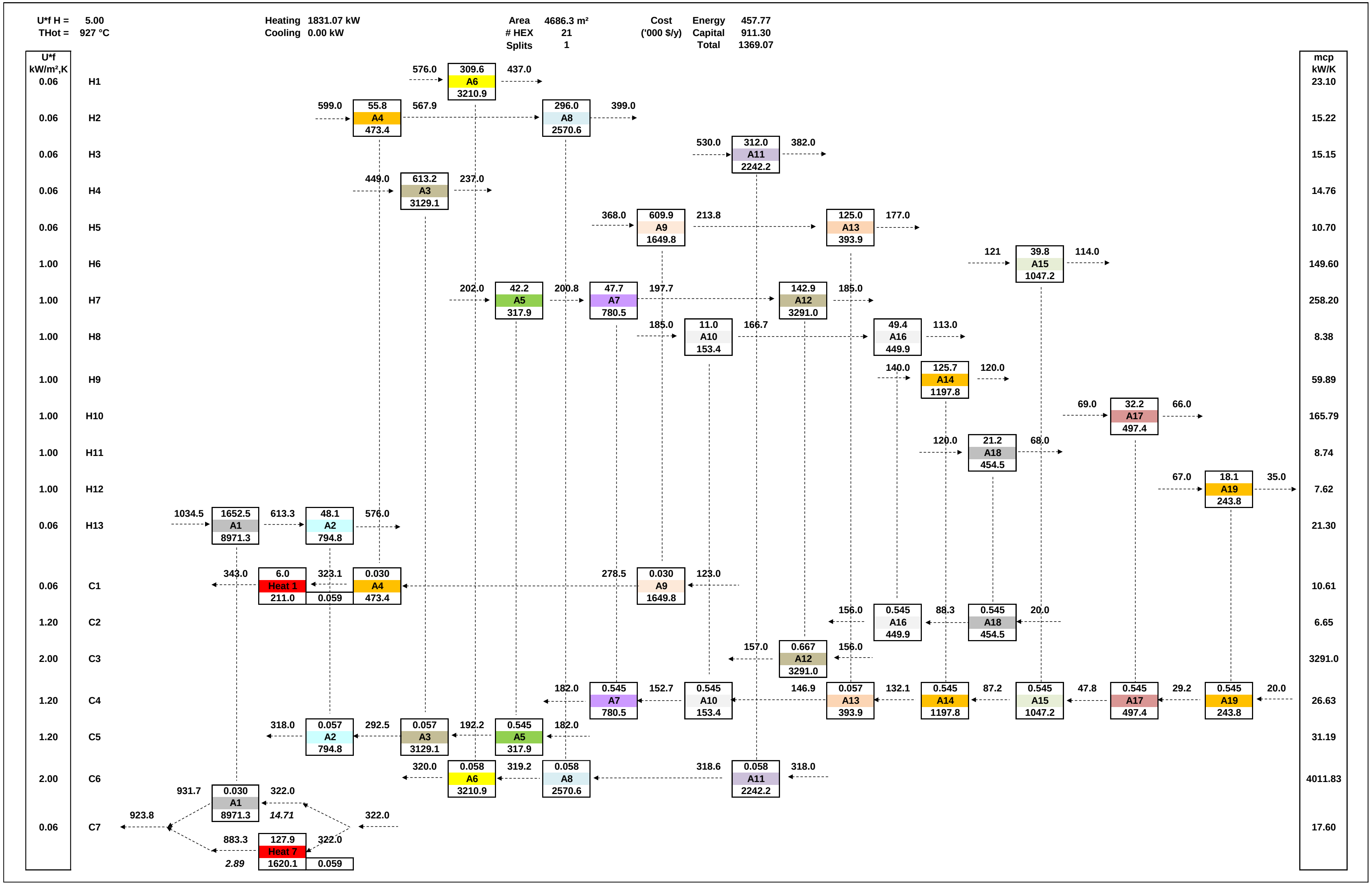

U*f H = 5.00
THot = 927 °C
Heating 1831.07 kW
Cooling 0.00 kW
Area 4686.3 m²
HEX 21
Splits 1
Cost ('000 $/y)
Energy 457.77
Capital 911.30
Total 1369.07
U*f kW/m²,K
mcp kW/K
0.06 H1 576.0 309.6 A6 3210.9 437.0 23.10
0.06 H2 599.0 55.8 A4 473.4 567.9 296.0 A8 2570.6 399.0 15.22
0.06 H3 530.0 312.0 A11 2242.2 382.0 15.15
0.06 H4 449.0 613.2 A3 3129.1 237.0 14.76
0.06 H5 368.0 609.9 A9 1649.8 213.8 125.0 A13 393.9 177.0 10.70
1.00 H6 121 39.8 A15 1047.2 114.0 149.60
1.00 H7 202.0 42.2 A5 317.9 200.8 47.7 A7 780.5 197.7 142.9 A12 3291.0 185.0 258.20
1.00 H8 185.0 11.0 A10 153.4 166.7 49.4 A16 449.9 113.0 8.38
1.00 H9 140.0 125.7 A14 1197.8 120.0 59.89
1.00 H10 69.0 32.2 A17 497.4 66.0 165.79
1.00 H11 120.0 21.2 A18 454.5 68.0 8.74
1.00 H12 67.0 18.1 A19 243.8 35.0 7.62
0.06 H13 1034.5 1652.5 A1 8971.3 613.3 48.1 A2 794.8 576.0 21.30
0.06 C1 343.0 6.0 Heat 1 211.0 323.1 0.059 0.030 A4 473.4 278.5 0.030 A9 1649.8 123.0 10.61
1.20 C2 156.0 0.545 A16 449.9 88.3 0.545 A18 454.5 20.0 6.65
2.00 C3 157.0 0.667 A12 3291.0 156.0 3291.0
1.20 C4 182.0 0.545 A7 780.5 152.7 0.545 A10 153.4 146.9 0.057 A13 393.9 132.1 0.545 A14 1197.8 87.2 0.545 A15 1047.2 47.8 0.545 A17 497.4 29.2 0.545 A19 243.8 20.0 26.63
1.20 C5 318.0 0.057 A2 794.8 292.5 0.057 A3 3129.1 192.2 0.545 A5 317.9 182.0 31.19
2.00 C6 320.0 0.058 A6 3210.9 319.2 0.058 A8 2570.6 318.6 0.058 A11 2242.2 318.0 4011.83
931.7 0.030 A1 8971.3 322.0 14.71
0.06 C7 923.8 322.0 17.60
883.3 127.9 Heat 7 1620.1 322.0 0.059 2.89

Figure 14.8

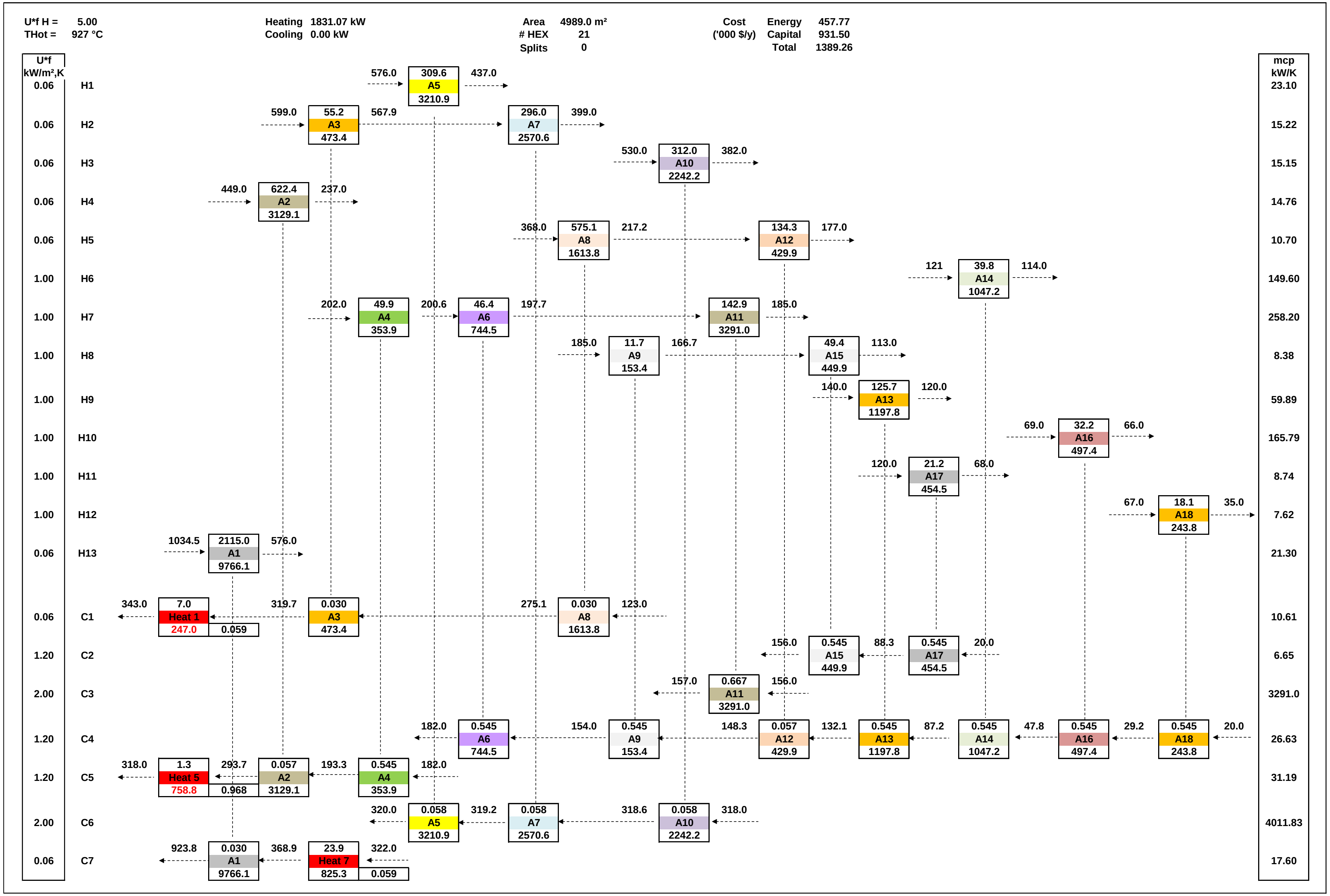

U*f H = 5.00
THot = 927 °C
Heating 1831.07 kW
Cooling 0.00 kW
Area 4989.0 m²
HEX 21
Splits 0
Cost ('000 $/y)
Energy 457.77
Capital 931.50
Total 1389.26
U*f kW/m²,K
mcp kW/K
H1 0.06 23.10
H2 0.06 15.22
H3 0.06 15.15
H4 0.06 14.76
H5 0.06 10.70
H6 1.00 149.60
H7 1.00 258.20
H8 1.00 8.38
H9 1.00 59.89
H10 1.00 165.79
H11 1.00 8.74
H12 1.00 7.62
H13 0.06 21.30
C1 0.06 10.61
C2 1.20 6.65
C3 2.00 3291.0
C4 1.20 26.63
C5 1.20 31.19
C6 2.00 4011.83
C7 0.06 17.60
576.0 309.6 A5 3210.9 437.0
599.0 55.2 A3 473.4 567.9 296.0 A7 2570.6 399.0
530.0 312.0 A10 2242.2 382.0
449.0 622.4 A2 3129.1 237.0
368.0 575.1 A8 1613.8 217.2 134.3 A12 429.9 177.0
121 39.8 A14 1047.2 114.0
202.0 49.9 A4 353.9 200.6 46.4 A6 744.5 197.7 142.9 A11 3291.0 185.0
185.0 11.7 A9 153.4 166.7 49.4 A15 449.9 113.0
140.0 125.7 A13 1197.8 120.0
69.0 32.2 A16 497.4 66.0
120.0 21.2 A17 454.5 68.0
67.0 18.1 A18 243.8 35.0
1034.5 2115.0 A1 9766.1 576.0
343.0 7.0 Heat 1 247.0 0.059 319.7 0.030 A3 473.4 275.1 0.030 A8 1613.8 123.0
156.0 0.545 A15 449.9 88.3 0.545 A17 454.5 20.0
157.0 0.667 A11 3291.0 156.0
182.0 0.545 A6 744.5 154.0 0.545 A9 153.4 148.3 0.057 A12 429.9 132.1 0.545 A13 1197.8 87.2 0.545 A14 1047.2 47.8 0.545 A16 497.4 29.2 0.545 A18 243.8 20.0
318.0 1.3 Heat 5 758.8 0.968 293.7 0.057 A2 3129.1 193.3 0.545 A4 353.9 182.0
320.0 0.058 A5 3210.9 319.2 0.058 A7 2570.6 318.6 0.058 A10 2242.2 318.0
923.8 0.030 A1 9766.1 368.9 23.9 Heat 7 825.3 0.059 322.0

Figure 14.09

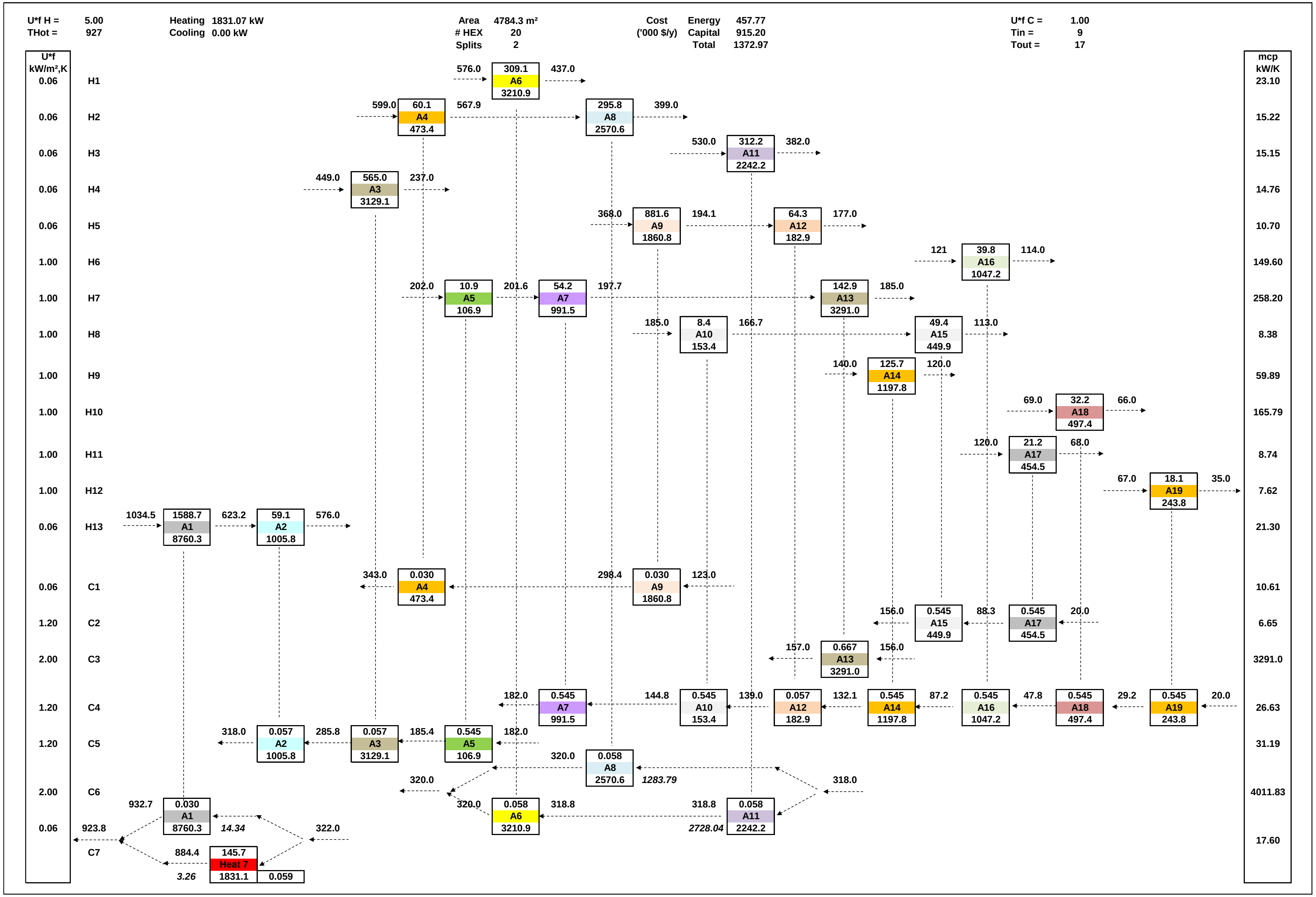

U*f H = 5.00
THot = 927
Heating 1831.07 kW
Cooling 0.00 kW
Area 4784.3 m²
HEX 20
Splits 2
Cost ('000 $/y)
Energy 457.77
Capital 915.20
Total 1372.97
U*f C = 1.00
Tin = 9
Tout = 17
U*f kW/m²,K
mcp kW/K
0.06 H1 576.0 309.1 A6 3210.9 437.0 23.10
0.06 H2 599.0 60.1 A4 473.4 567.9 295.8 A8 2570.6 399.0 15.22
0.06 H3 530.0 312.2 A11 2242.2 382.0 15.15
0.06 H4 449.0 565.0 A3 3129.1 237.0 14.76
0.06 H5 368.0 881.6 A9 1860.8 194.1 64.3 A12 182.9 177.0 10.70
1.00 H6 121 39.8 A16 1047.2 114.0 149.60
1.00 H7 202.0 10.9 A5 106.9 201.6 54.2 A7 991.5 197.7 142.9 A13 3291.0 185.0 258.20
1.00 H8 185.0 8.4 A10 153.4 166.7 49.4 A15 449.9 113.0 8.38
1.00 H9 140.0 125.7 A14 1197.8 120.0 59.89
1.00 H10 69.0 32.2 A18 497.4 66.0 165.79
1.00 H11 120.0 21.2 A17 454.5 68.0 8.74
1.00 H12 67.0 18.1 A19 243.8 35.0 7.62
0.06 H13 1034.5 1588.7 A1 8760.3 623.2 59.1 A2 1005.8 576.0 21.30
0.06 C1 343.0 0.030 A4 473.4 298.4 0.030 A9 1860.8 123.0 10.61
1.20 C2 156.0 0.545 A15 449.9 88.3 0.545 A17 454.5 20.0 6.65
2.00 C3 157.0 0.667 A13 3291.0 156.0 3291.0
1.20 C4 182.0 0.545 A7 991.5 144.8 0.545 A10 153.4 139.0 0.057 A12 182.9 132.1 0.545 A14 1197.8 87.2 0.545 A16 1047.2 47.8 0.545 A18 497.4 29.2 0.545 A19 243.8 20.0 26.63
1.20 C5 318.0 0.057 A2 1005.8 285.8 0.057 A3 3129.1 185.4 0.545 A5 106.9 182.0 31.19
2.00 C6 320.0 0.058 A8 2570.6 1283.79 320.0 318.0 4011.83
932.7 0.030 A1 8760.3 14.34 320.0 0.058 A6 3210.9 318.8 318.8 0.058 A11 2242.2 2728.04
0.06 923.8 322.0 17.60
C7 884.4 145.7 Heat 7 1831.1 0.059 3.26

Figure 14.10

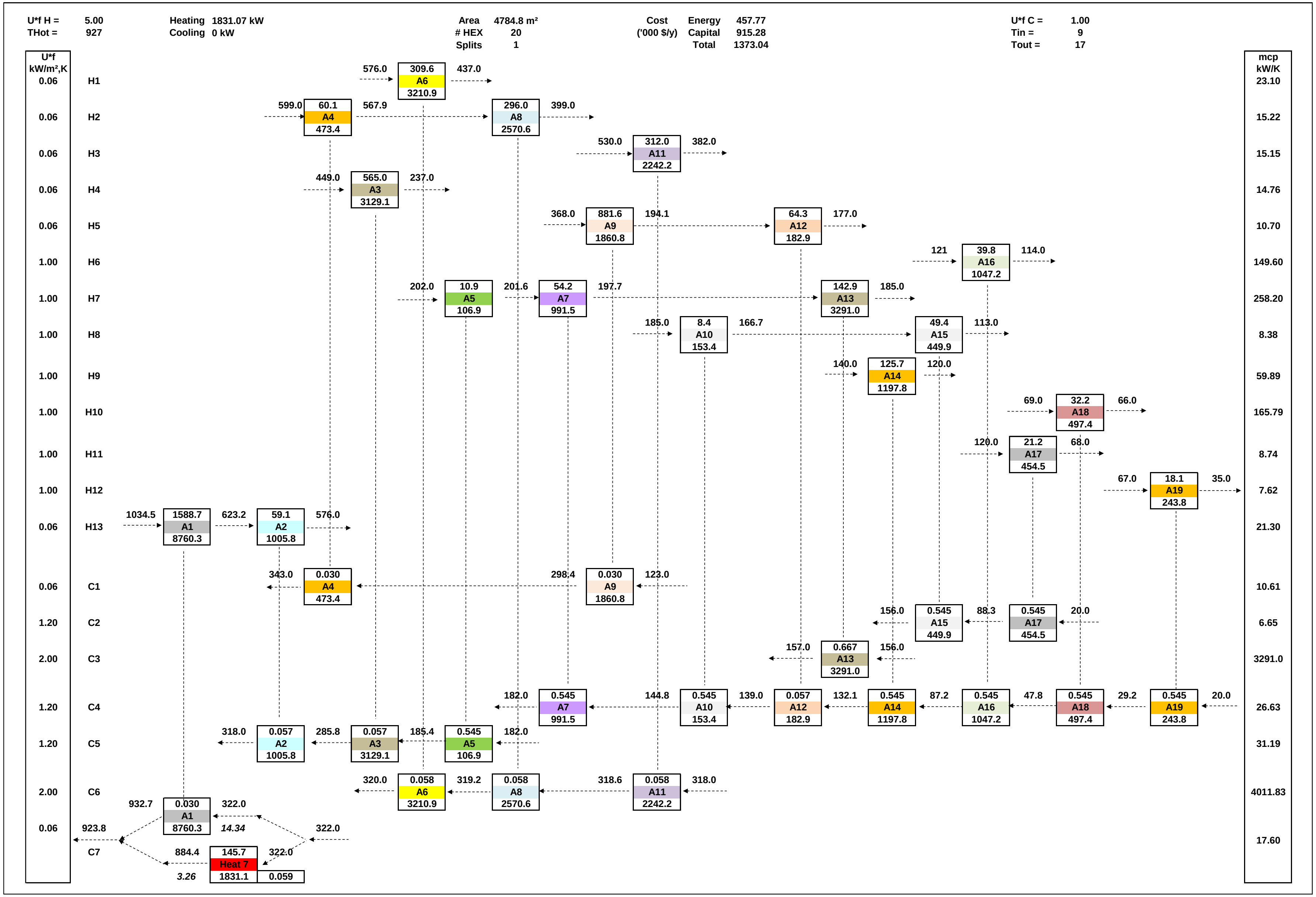

U*f H = 5.00
THot = 927
Heating 1831.07 kW
Cooling 0 kW
Area 4784.8 m²
HEX 20
Splits 1
Cost ('000 $/y)
Energy 457.77
Capital 915.28
Total 1373.04
U*f C = 1.00
Tin = 9
Tout = 17
U*f kW/m²,K
mcp kW/K
H1 0.06 23.10
H2 0.06 15.22
H3 0.06 15.15
H4 0.06 14.76
H5 0.06 10.70
H6 1.00 149.60
H7 1.00 258.20
H8 1.00 8.38
H9 1.00 59.89
H10 1.00 165.79
H11 1.00 8.74
H12 1.00 7.62
H13 0.06 21.30
C1 0.06 10.61
C2 1.20 6.65
C3 2.00 3291.0
C4 1.20 26.63
C5 1.20 31.19
C6 2.00 4011.83
C7 0.06 17.60
576.0 309.6 A6 3210.9 437.0
599.0 60.1 A4 473.4 567.9 296.0 A8 2570.6 399.0
530.0 312.0 A11 2242.2 382.0
449.0 565.0 A3 3129.1 237.0
368.0 881.6 A9 1860.8 194.1 64.3 A12 182.9 177.0
121 39.8 A16 1047.2 114.0
202.0 10.9 A5 106.9 201.6 54.2 A7 991.5 197.7 142.9 A13 3291.0 185.0
185.0 8.4 A10 153.4 166.7 49.4 A15 449.9 113.0
140.0 125.7 A14 1197.8 120.0
69.0 32.2 A18 497.4 66.0
120.0 21.2 A17 454.5 68.0
67.0 18.1 A19 243.8 35.0
1034.5 1588.7 A1 8760.3 623.2 59.1 A2 1005.8 576.0
343.0 0.030 A4 473.4 298.4 0.030 A9 1860.8 123.0
156.0 0.545 A15 449.9 88.3 0.545 A17 454.5 20.0
157.0 0.667 A13 3291.0 156.0
182.0 0.545 A7 991.5 144.8 0.545 A10 153.4 139.0 0.057 A12 182.9 132.1 0.545 A14 1197.8 87.2 0.545 A16 1047.2 47.8 0.545 A18 497.4 29.2 0.545 A19 243.8 20.0
318.0 0.057 A2 1005.8 285.8 0.057 A3 3129.1 185.4 0.545 A5 106.9 182.0
320.0 0.058 A6 3210.9 319.2 0.058 A8 2570.6 318.6 0.058 A11 2242.2 318.0
932.7 0.030 A1 8760.3 322.0 14.34
923.8 322.0
884.4 145.7 Heat 7 1831.1 0.059 322.0
3.26

Figure 14.11

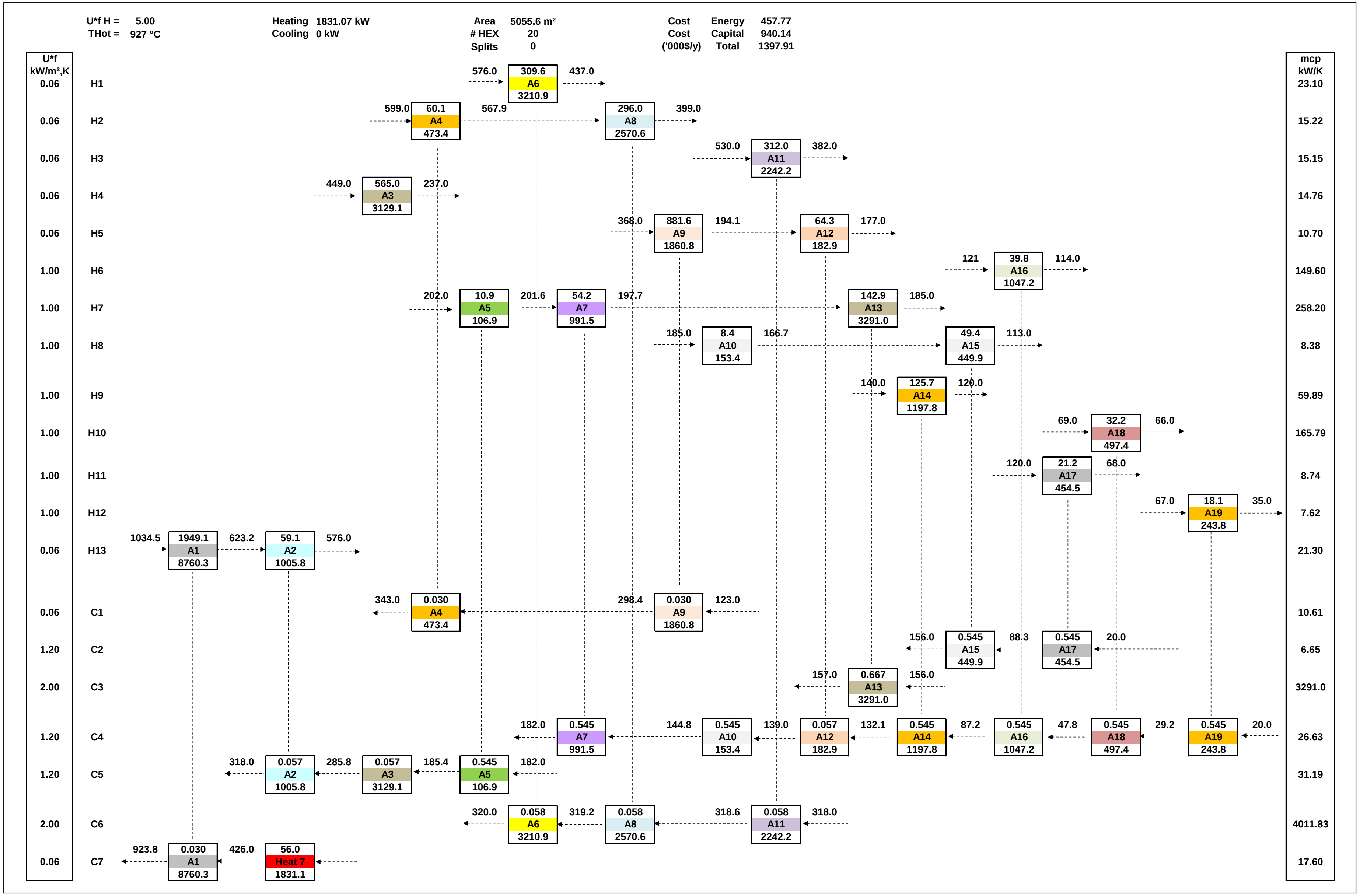

U*f H = 5.00
THot = 927 °C
Heating 1831.07 kW
Cooling 0 kW
Area 5055.6 m²
HEX 20
Splits 0
Cost ('000$/y)
Energy 457.77
Capital 940.14
Total 1397.91
U*f kW/m²,K
mcp kW/K
H1 0.06 23.10
H2 0.06 15.22
H3 0.06 15.15
H4 0.06 14.76
H5 0.06 10.70
H6 1.00 149.60
H7 1.00 258.20
H8 1.00 8.38
H9 1.00 59.89
H10 1.00 165.79
H11 1.00 8.74
H12 1.00 7.62
H13 0.06 21.30
C1 0.06 10.61
C2 1.20 6.65
C3 2.00 3291.0
C4 1.20 26.63
C5 1.20 31.19
C6 2.00 4011.83
C7 0.06 17.60
576.0 309.6 A6 3210.9 437.0
599.0 60.1 A4 473.4 567.9 296.0 A8 2570.6 399.0
530.0 312.0 A11 2242.2 382.0
449.0 565.0 A3 3129.1 237.0
368.0 881.6 A9 1860.8 194.1 64.3 A12 182.9 177.0
121 39.8 A16 1047.2 114.0
202.0 10.9 A5 106.9 201.6 54.2 A7 991.5 197.7 142.9 A13 3291.0 185.0
185.0 8.4 A10 153.4 166.7 49.4 A15 449.9 113.0
140.0 125.7 A14 1197.8 120.0
69.0 32.2 A18 497.4 66.0
120.0 21.2 A17 454.5 68.0
67.0 18.1 A19 243.8 35.0
1034.5 1949.1 A1 8760.3 623.2 59.1 A2 1005.8 576.0
343.0 0.030 A4 473.4 298.4 0.030 A9 1860.8 123.0
156.0 0.545 A15 449.9 88.3 0.545 A17 454.5 20.0
157.0 0.667 A13 3291.0 156.0
182.0 0.545 A7 991.5 144.8 0.545 A10 153.4 139.0 0.057 A12 182.9 132.1 0.545 A14 1197.8 87.2 0.545 A16 1047.2 47.8 0.545 A18 497.4 29.2 0.545 A19 243.8 20.0
318.0 0.057 A2 1005.8 285.8 0.057 A3 3129.1 185.4 0.545 A5 106.9 182.0
320.0 0.058 A6 3210.9 319.2 0.058 A8 2570.6 318.6 0.058 A11 2242.2 318.0
923.8 0.030 A1 8760.3 426.0 56.0 Heat 7 1831.1

Figure 14.12

15 The Crude Fractionation Unit from Kim and Bagajewicz

This crude fractionation unit case was presented by Kim et al. in 2016 [123] and 2017 [32]. It has also been treated by Pavão et al. [33] and Nair and Karimi [110]. The case has also intensively been studied by this author in Case 24, Benchmark Solutions for a Crude Fractionation Unit [124].
The stream data and financial parameters are shown in Table 15.1.

Table 15.1

Tsupply	Ttarget	Heat	DT-shift	U*f	Descript.	mcp
°C	°C	kW	K	kW/K,m²	-	kW/K
360.0	290.0	2786.7	1.0	0.47	VR1	39.81
290.0	115.0	6966.8	1.0	0.47	VR2	39.81
303.6	270.2	7848.3	3.0	0.41	LCR	234.98
359.6	280.0	1952.6	1.0	0.47	SR-Quench	24.53
250.6	90.0	21231.3	4.0	0.26	HVGO	132.2
248.8	110.0	4415.2	-1.0	0.72	LGO	31.81
277.0	121.9	3812.4	0.0	0.57	HGO	24.58
210.0	163.0	5440.7	3.0	0.33	MCR	115.76
170.1	60.0	3735.7	0.0	0.45	Kerosene	33.93
140.2	39.5	10724.6	5.0	0.26	TCR	106.5
178.6	108.9	3335.1	-1.0	0.60	LVGO	47.85
30.0	130.0	20248.0	0.0	0.26	Crude 1	202.48
130.0	350.0	63782.4	0.0	0.72	Crude 2	289.92
500.0	499.0	20375.0		0.53	Heating	
20.0	40.0	8593.98		0.53	Cooling	

Financial parameters

Heating : 100.0 $/kW,year Cooling : 10.0 $/kW,year

HEX cost : 25 000 + 55.0 x Area $/year

It is not clear what kind of hot utility has been used: steam does not condense at the given temperature level and flue gas would have a different temperature profile. The temperatures were maintained, however, to allow comparison with results from other studies and, furthermore, they have no real impact on the results.

The heating load has been chosen on the basis of the trade-off curve in Figure 15.1. Shift values were optimized by crisscross optimization for minimum cost. Composite curves are shown in Figure 15.2. The pinch is caused by hot stream MRC; the minimum number of units is 18 for a system segregated at the pinch.

From practical point of view, it might be interesting to split the network not at the pinch, but at 130°C, the supply temperature of the high-temperature crude section after the desalter. With the split at that level, however, both the kerosene and the LVGO would have a small exchanger above and one below the desalter, which would increase the number of units from 18 to 19. This has been avoided in the trade-off analysis by pushing these streams down to below the desalter level by applying an increased shift on those streams, resulting in the green curve in Figure 15.1. The number of units in the analysis drops from 18 to 17, whilst the area goes up with 478 m² from 12944 m² to 13422 m². The additional area cost of 26290 $/y is quasi compensated by avoiding one unit, saving 25000 $/y and, expectedly, the network will be simpler. The costs of the 2 alternatives are compared in Table 15.2. The difference between vertical and criss-cross area is only 1.0%, due to the small shift values.

Further analysis of the grid indicates that the cooling can be concentrated in one unit on the TCR and suggests putting all hot streams below the desalter on parallel branches of the crude. Herewith, the initial network below the desalter can be synthesised with the target number of units of 8.

The grid above the desalter can be reduced to 7 bands with 21 units (using LP) and herewith an initial network can de designed for further optimisation. Application of incremental evolution and smart optimisation procedures with non-isothermal splits will reduce the network to 17 units with an area of 13398 m², 11 splits and an annual cost of 3328.57 k$/year (Figure 14.4). As indicated in that figure, this network can be fine-tuned by alternating the pipe connections between exchangers A1 through A5 and further optimised, leading to the network of Figure 14.5 with 10 splits and a cost of 3324.61 k$/year.

That network can be further improved and simplified by reducing the number of splits. Above the desalter, the 5 streams VR2, HVGO, LGO, HGO and MCR must be cooled down with branches of the crude above the desalter to stay close to the energy target. Consequently, the crude above the desalter remains split in 5 branches. Below the desalter, however, the number of branches can be reduced by merging branches or by replacing an exchanger on a branch with a cooler. In finding optimum solutions, the following additional heuristics were tested:

- Move the heat exchanger with the smallest heat transfer coefficient to the cold side with larger driving force,
- Increase the load on that branch by adding other loads and increasing the split ratio on that branch to increase the driving force.

The results of application of said heuristics are shown in Figure 15.3.

So far, the above networks had no minimum approach temperature (EMAT). To enable full comparison with the network by Kim in [32], an EMAT of 10 °C was imposed on the previous networks. These results are also shown in Figure 15.3.

The results are summarised and compared with published results in Table 15.3. Optimum networks have 17 units and 9 splits. They are shown in Figure 15.5 (EMAT of 10 K), respectively Figure 15.6 (no EMAT). The full list of networks with splits from 4 to 10 can be found in [124].

All networks, except those with only 4 splits, have a cost within less than 0.8 % of the optimum. There exist more than 50 networks with a cost range within 0.5% of the optimum.

Conclusion: targeting with insight in the process combined with simple procedures enables synthesis of competitive heat exchanger network structures

Table 15.2

Results Pinch analysis			
InputUtil.Hot/Cold	kW	20375.00	8593.98
HEX area (vertical):	m²	13059.61	
HEX area (criss-cross):	m²	12943.94	
Annual cost utilities	'000 $/y	2123.44	

Pinched at 210°C (MCR)			
HEX area (criss-cross):	m²	12943.94	
Feasible # units above/below Pinch :		8	10
Annual cost Investment	'000 $/y	1161.92	
Total annual cost	'000 $/y	3285.36	

Split at 130°C and KERO and LVGO pushed down			
HEX area (criss-cross):	m²	13421.97	
Feasible # units above/below split:		9	8
Annual cost Investment	'000 $/y	1163.21	
Total annual cost	'000 $/y	3286.65	

Table 15.3

	Heating	Cooling	Area	Units	Splits	Utility cost	Area cost	Total cost
	kW	kW	m²	-	-	'000 $/y	'000 $/y	'000 $/y
EMAT 10 K								
Kim et al. (best of) °)	23 566	11 783	9 794	17	6	2 474.43	982.22	3 456.65
Kim et al. °°)	23 566	11 785	10 044	17	6	2 474.45	977.40	3 451.85
°) reported	°°) recalculated and optimised							
This research	21 034	9 253	12 945	17	10	2 195.93	1 136.98	3 332.91
	21 017	9 236	12 942	17	9	2 194.06	1 136.79	3 330.85
	21 017	9 236	12 949	17	8	2 194.06	1 137.17	3 331.23
	21 021	9 240	12 982	17	7	2 194.50	1 139.00	3 333.50
	21 066	9 285	13 007	17	6	2 199.45	1 140.39	3 339.84
	21 177	9 396	13 060	17	5	2 211.66	1 143.30	3 354.96
	21 468	9 687	13 088	19	4	2 243.67	1 194.82	3 438.49
no EMAT								
Pavão et al.	20 891	9108	13 835	18	7	2180.18	1 210.89	3 391.07
Nair et al. (best of)	20 894	9114	13 432	17	10	2180.54	1 163.78	3 344.32
This research	20 747	8 966	13 368	17	10	2 164.36	1 160.25	3 324.61
	20 705	8 924	13 396	17	9	2 159.74	1 161.79	3 321.53
	20 710	8 929	13 393	17	8	2 160.29	1 161.64	3 321.93
	20 717	8 936	13 433	17	7	2 161.06	1 163.80	3 324.86
	20 795	9 014	13 409	17	6	2 169.64	1 162.47	3 332.11
	20 908	9 127	13 472	17	5	2 182.07	1 165.95	3 348.02
	21 224	9 443	13 763	18	4	2 216.83	1 206.95	3 423.78

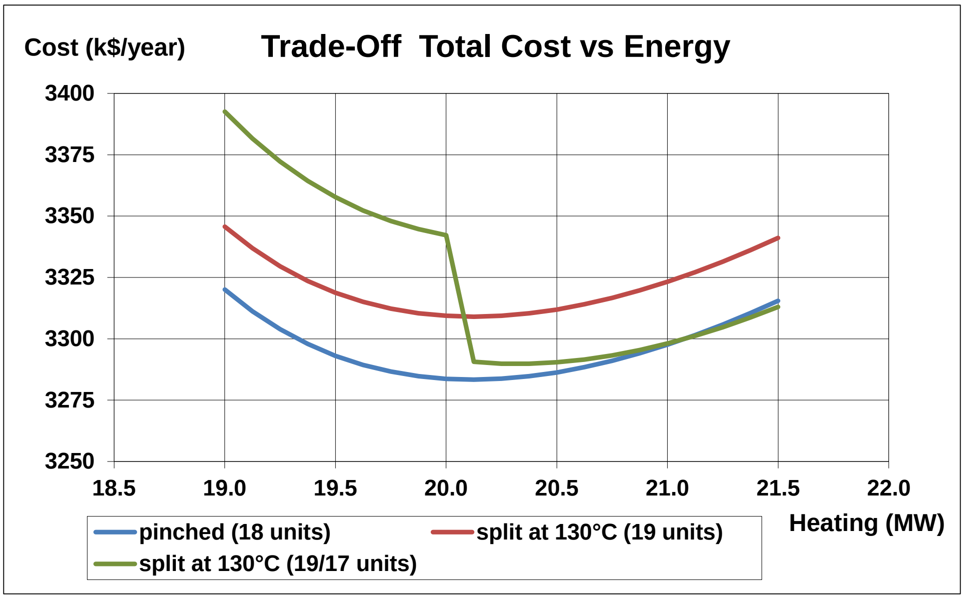


Figure 15.1

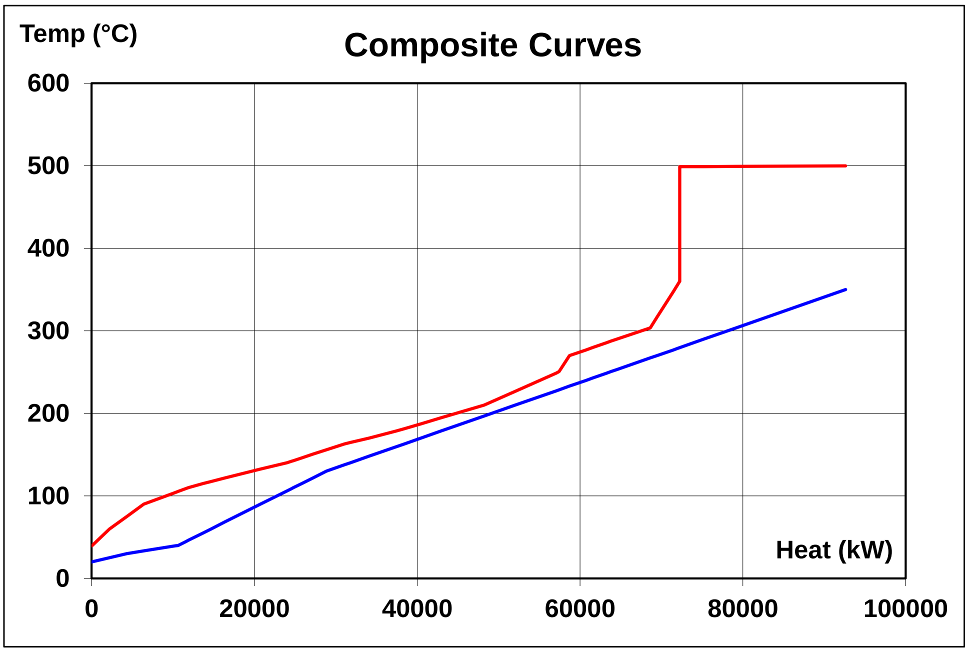


Figure 15.2

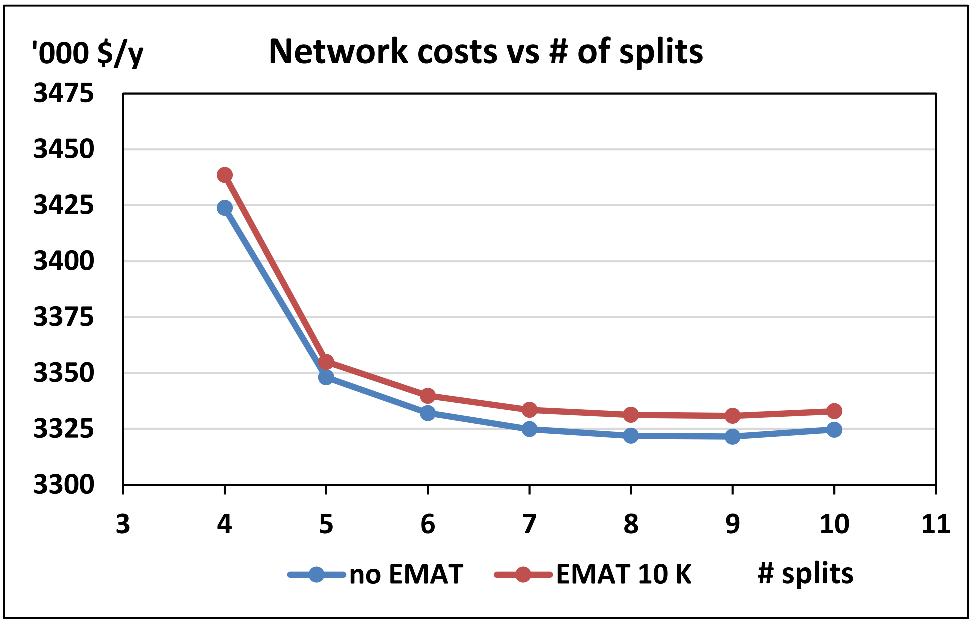


Figure 15.3

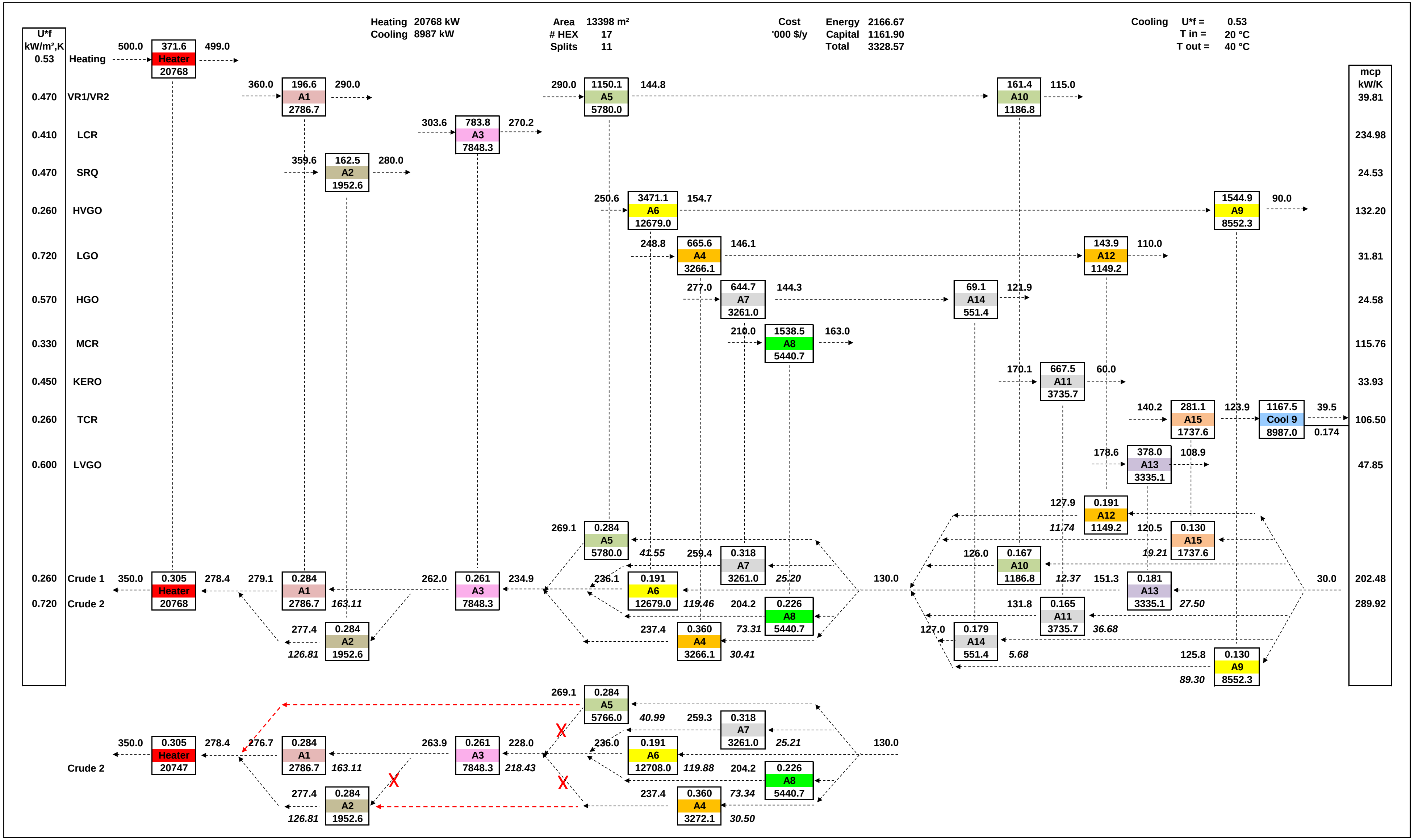

Heating 20768 kW
Cooling 8987 kW
Area 13398 m²
HEX 17
Splits 11
Cost '000 $/y
Energy 2166.67
Capital 1161.90
Total 3328.57
Cooling U*f = 0.53
T in = 20 °C
T out = 40 °C
U*f kW/m²,K
mcp kW/K
0.53 Heating
0.470 VR1/VR2 39.81
0.410 LCR 234.98
0.470 SRQ 24.53
0.260 HVGO 132.20
0.720 LGO 31.81
0.570 HGO 24.58
0.330 MCR 115.76
0.450 KERO 33.93
0.260 TCR 106.50
0.600 LVGO 47.85
0.260 Crude 1 202.48
0.720 Crude 2 289.92
500.0
371.6
Heater
20768
499.0
360.0
196.6
A1
2786.7
290.0
303.6
783.8
A3
7848.3
270.2
359.6
162.5
A2
1952.6
280.0
290.0
1150.1
A5
5780.0
144.8
161.4
A10
1186.8
115.0
250.6
3471.1
A6
12679.0
154.7
1544.9
A9
8552.3
90.0
248.8
665.6
A4
3266.1
146.1
143.9
A12
1149.2
110.0
277.0
644.7
A7
3261.0
144.3
69.1
A14
551.4
121.9
210.0
1538.5
A8
5440.7
163.0
170.1
667.5
A11
3735.7
60.0
140.2
281.1
A15
1737.6
123.9
1167.5
Cool 9
8987.0
39.5
0.174
178.6
378.0
A13
3335.1
108.9
127.9
0.191
A12
1149.2
11.74
269.1
0.284
A5
5780.0
41.55
259.4
0.318
A7
3261.0
25.20
120.5
0.130
A15
1737.6
19.21
126.0
0.167
A10
1186.8
12.37
151.3
0.181
A13
3335.1
27.50
350.0
0.305
Heater
20768
278.4
279.1
0.284
A1
2786.7
163.11
262.0
0.261
A3
7848.3
234.9
236.1
0.191
A6
12679.0
119.46
204.2
0.226
A8
5440.7
130.0
30.0
131.8
0.165
A11
3735.7
36.68
277.4
0.284
A2
1952.6
126.81
237.4
0.360
A4
3266.1
73.31
30.41
127.0
0.179
A14
551.4
5.68
125.8
0.130
A9
8552.3
89.30
269.1
0.284
A5
5766.0
40.99
259.3
0.318
A7
3261.0
25.21
X
Crude 2
350.0
0.305
Heater
20747
278.4
276.7
0.284
A1
2786.7
163.11
263.9
0.261
A3
7848.3
228.0
218.43
236.0
0.191
A6
12708.0
119.88
204.2
0.226
A8
5440.7
130.0
X
X
277.4
0.284
A2
1952.6
126.81
237.4
0.360
A4
3272.1
73.34
30.50

Figure 15.4

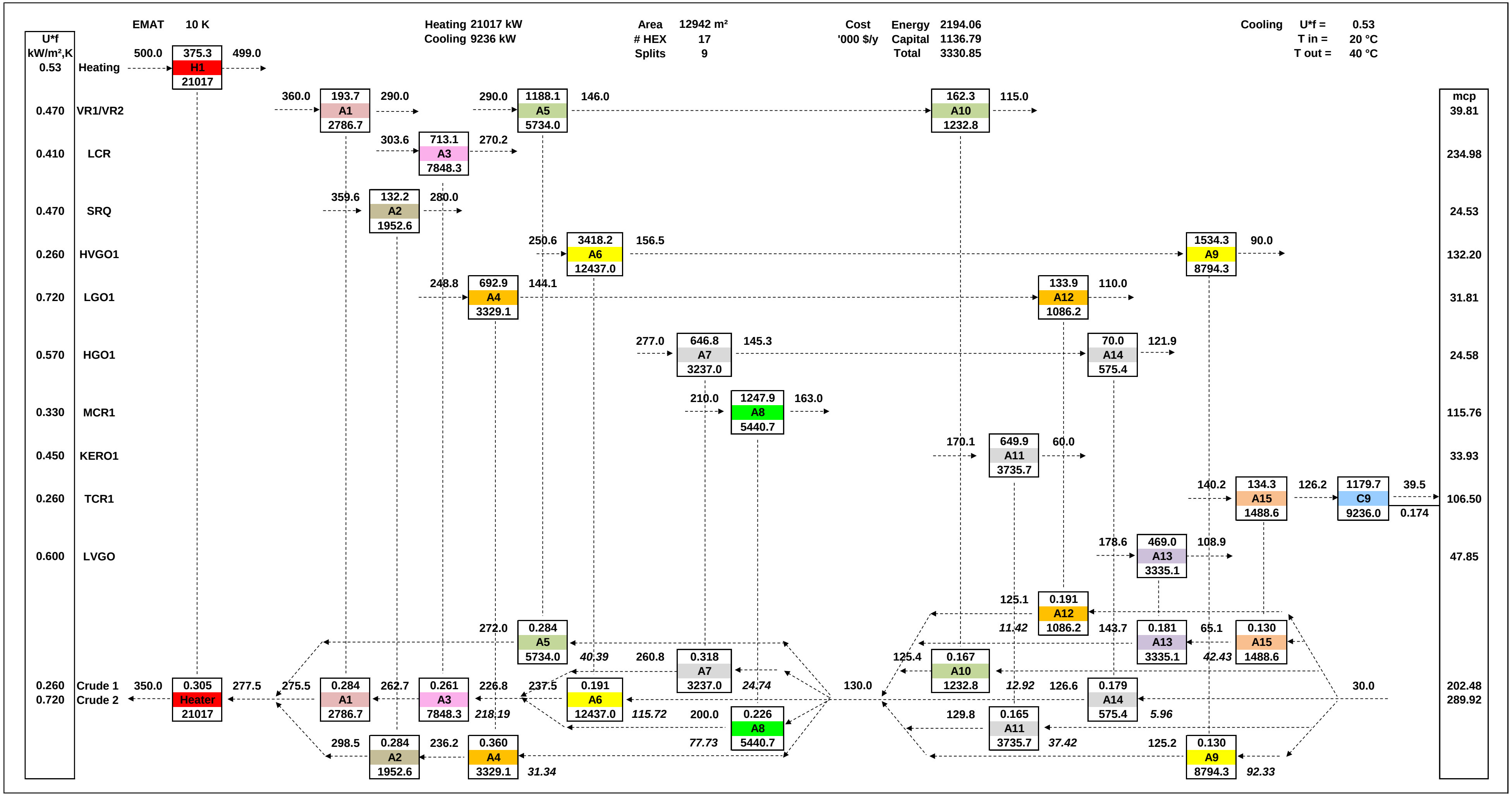

EMAT 10 K
Heating 21017 kW
Cooling 9236 kW
Area 12942 m²
HEX 17
Splits 9
Cost '000 $/y
Energy 2194.06
Capital 1136.79
Total 3330.85
Cooling U*f = 0.53
T in = 20 °C
T out = 40 °C
U*f kW/m²,K
0.53 Heating
0.470 VR1/VR2
0.410 LCR
0.470 SRQ
0.260 HVGO1
0.720 LGO1
0.570 HGO1
0.330 MCR1
0.450 KERO1
0.260 TCR1
0.600 LVGO
0.260 Crude 1
0.720 Crude 2
mcp
39.81
234.98
24.53
132.20
31.81
24.58
115.76
33.93
106.50
47.85
202.48
289.92
500.0
375.3
H1
21017
499.0
360.0
193.7
A1
2786.7
290.0
290.0
1188.1
A5
5734.0
146.0
162.3
A10
1232.8
115.0
303.6
713.1
A3
7848.3
270.2
359.6
132.2
A2
1952.6
280.0
250.6
3418.2
A6
12437.0
156.5
1534.3
A9
8794.3
90.0
248.8
692.9
A4
3329.1
144.1
133.9
A12
1086.2
110.0
277.0
646.8
A7
3237.0
145.3
70.0
A14
575.4
121.9
210.0
1247.9
A8
5440.7
163.0
170.1
649.9
A11
3735.7
60.0
140.2
134.3
A15
1488.6
126.2
1179.7
C9
9236.0
39.5
0.174
178.6
469.0
A13
3335.1
108.9
125.1
0.191
A12
1086.2
11.42
143.7
0.181
A13
3335.1
65.1
0.130
A15
1488.6
42.43
272.0
0.284
A5
5734.0
40.39
260.8
0.318
A7
3237.0
24.74
125.4
0.167
A10
1232.8
350.0
0.305
Heater
21017
277.5
275.5
0.284
A1
2786.7
262.7
0.261
A3
7848.3
226.8
218.19
237.5
0.191
A6
12437.0
115.72
200.0
0.226
A8
5440.7
77.73
130.0
12.92
126.6
0.179
A14
575.4
5.96
30.0
129.8
0.165
A11
3735.7
37.42
298.5
0.284
A2
1952.6
236.2
0.360
A4
3329.1
31.34
125.2
0.130
A9
8794.3
92.33

Figure 15.5

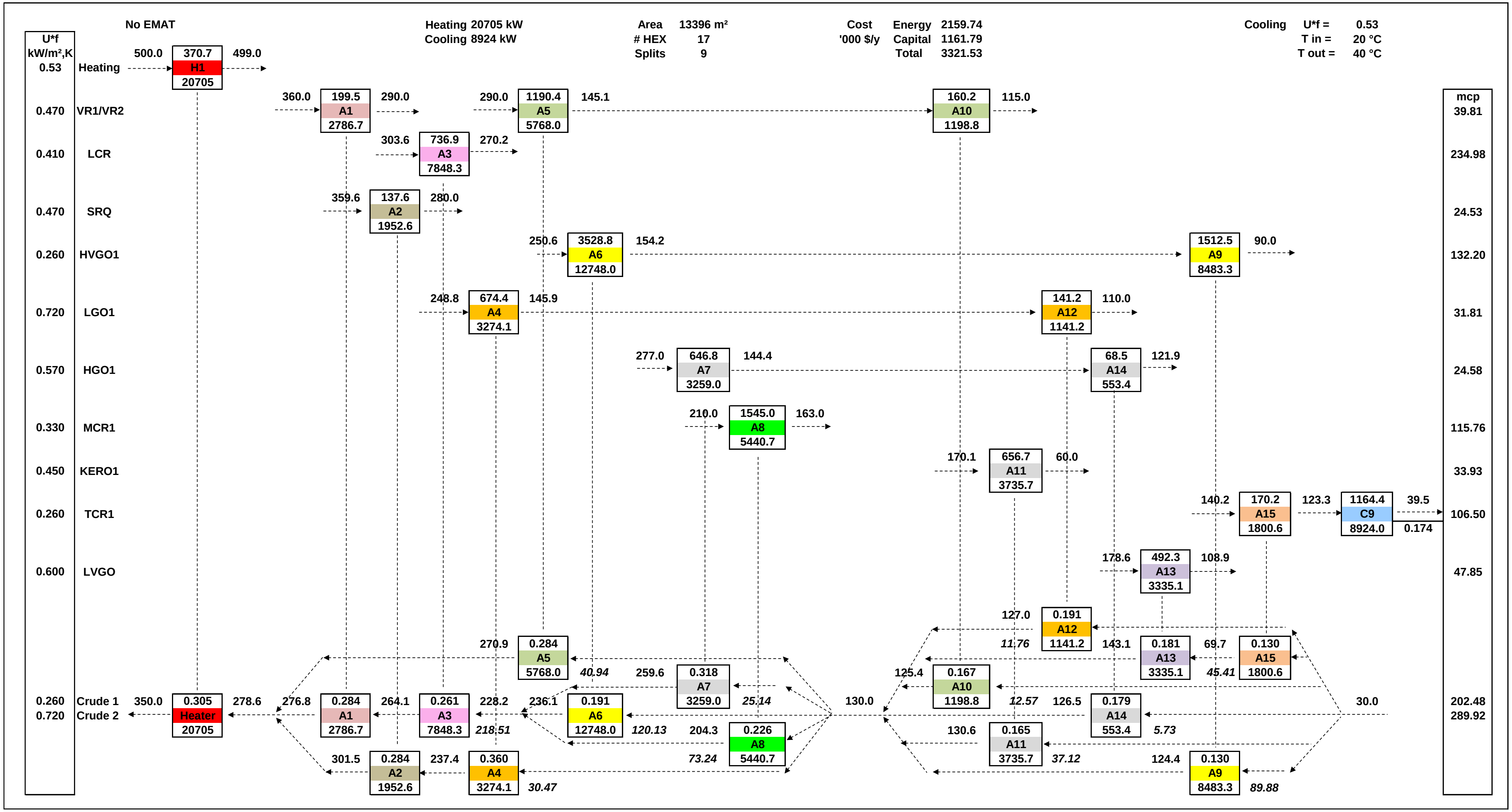

No EMAT
Heating 20705 kW
Cooling 8924 kW
Area 13396 m²
HEX 17
Splits 9
Cost '000 $/y
Energy 2159.74
Capital 1161.79
Total 3321.53
Cooling U*f = 0.53
T in = 20 °C
T out = 40 °C
U*f kW/m²,K
0.53 Heating
500.0
370.7 H1 20705
499.0
0.470 VR1/VR2
360.0
199.5 A1 2786.7
290.0
290.0
1190.4 A5 5768.0
145.1
160.2 A10 1198.8
115.0
mcp
39.81
0.410 LCR
303.6
736.9 A3 7848.3
270.2
234.98
0.470 SRQ
359.6
137.6 A2 1952.6
280.0
24.53
0.260 HVGO1
250.6
3528.8 A6 12748.0
154.2
1512.5 A9 8483.3
90.0
132.20
0.720 LGO1
248.8
674.4 A4 3274.1
145.9
141.2 A12 1141.2
110.0
31.81
0.570 HGO1
277.0
646.8 A7 3259.0
144.4
68.5 A14 553.4
121.9
24.58
0.330 MCR1
210.0
1545.0 A8 5440.7
163.0
115.76
0.450 KERO1
170.1
656.7 A11 3735.7
60.0
33.93
0.260 TCR1
140.2
170.2 A15 1800.6
123.3
1164.4 C9 8924.0
39.5
0.174
106.50
0.600 LVGO
178.6
492.3 A13 3335.1
108.9
47.85
127.0
0.191 A12 1141.2
11.76
270.9
0.284 A5 5768.0
40.94
259.6
0.318 A7 3259.0
25.14
143.1
0.181 A13 3335.1
69.7
45.41
0.130 A15 1800.6
125.4
0.167 A10 1198.8
12.57
0.260 Crude 1
0.720 Crude 2
350.0
0.305 Heater 20705
278.6
276.8
0.284 A1 2786.7
264.1
0.261 A3 7848.3
228.2
218.51
236.1
0.191 A6 12748.0
120.13
204.3
0.226 A8 5440.7
73.24
130.0
126.5
0.179 A14 553.4
5.73
130.6
0.165 A11 3735.7
37.12
30.0
202.48
289.92
301.5
0.284 A2 1952.6
237.4
0.360 A4 3274.1
30.47
124.4
0.130 A9 8483.3
89.88

Figure 15.6

16 The 9 streams problem from Faria, Kim and Bagajewicz

The original data set of this 9 streams example was reported as 10SP1 by Cerda 10 1980 [126] and was studied by Papoulias and Grossmann in 1983 [127]. The problem was then revisited, however, with a different data set: hot stream H9 was redefined as hot utility and heat loads were only 30% of the original. This data set was treated by Faria et al. in 2015 [128], by Kim and Bagajewicz in 2016 [123] and 2017 [129] and by Nair and Karimi in 2019 [110]. It was also studied by this author [125].

The 9 streams data set and financial parameters are given in Table 16.1.

Table 16.1

Tsupply	Ttarget	Heat	DT-shift	U*f	Descript.	mcp
K	K	kW	K	kW/K,m²	-	kW/K
500.15	339.15	713.39	5	0.06	H1	4.431
472.15	339.15	707.43	5	0.06	H2	5.319
522.15	411.15	350.98	5	0.06	H3	3.162
433.15	366.15	176.48	5	0.06	H4	2.634
355.15	450.15	492.48	5	0.06	C1	5.184
366.15	478.15	467.04	5	0.06	C2	4.170
311.15	494.15	463.36	5	0.06	C3	2.532
333.15	433.15	228.6	5	0.06	C4	2.286
389.15	495.15	193.34	5	0.06	C5	1.824
544.15	422.15	11.91	5	0.06	Heating	
311.15	355.15	115.37	5	0.06	Cooling	

Financial parameters

Heating : 566167 $/kW,year   Cooling : 53349 $/kW,year

HEX cost : 5 291.9 + 77.8 x Area $/year

A minimum value of 10 K as EMAT (exchanger minimum approach temperature) is imposed.

The utilities costs for this case are extremely high and would suggest a very specific application environment. A comment with the study by Cerda reads as follows: "*The material contained in this document is based upon work supported by a National Aeronautics and Space Administration (NASA) grant or cooperative agreement* ". This comment might explain the extraordinary level of utilities cost.

Results of the Pinch Analysis are given in Table 16.2.

Table 16.2

Pinch Temperature THot/Tcold streams (K):			376.15	366.15
Pinch caused by stream N#			6	Cold stream
Minimum Heating / Cooling (kW) :			11.91	115.37
Feasible # units above/below Pinch :			9	6
		Total	Above	Below Pinch
HEX area :	m²	4137.96	3269.35	868.61
Cost Utilities :	*000 $/y	12896.50	6741.75	6154.75
Cost Investment :	*000 $/y	401.27	301.95	99.32
Total Cost :	*000 $/y	13297.77		

The composite curves are shown in Figure 16.1. The curves are parallel over a wide range; the pinch is caused by cold stream C2. Trade of between energy and capital is shown in Figure 16.2. The analysis further indicates that the problem can be turned into a threshold problem (without heating) if an EMAT of 9.0385 K is applied; in such case, the cost target would go down from 13298 k$/year to 5933 k$/year.

Three alternative routes have been worked out.

a) First route.

A grid diagram is generated using the pinch analysis tool, resulting in a scheme with 16 integration bands. A design with an LP program generates a network satisfying energy and area targets, however, with 83 heat exchanger units; that number has to be reduced. To simplify the task, the number of integration bands is reduced from 16 to 7 by merging adjacent bands, without significantly changing the nature of the problem (Table 16.3).

Table 16.3 – Reduced Grid diagram

Descript.	Heat	mcp	Bands														
-	kW	kW/K		1		2		3		4	Pinch	5		6		7	
Heating	11.908	0.10	544.15		500.87		472.15		422.15								
H1	713.39	4.43			500.15		472.15		411.15		376.15		367.27		350.78		339.15
H2	707.43	5.32					472.15		411.15		376.15		367.27		350.78		339.15
H3	350.98	3.16	522.15		500.87		472.15		411.15								
H4	176.48	2.63							433.15		376.15		366.15				
C1	492.48	5.18					450.15		400.82		366.15		355.15				
C2	467.04	4.17			478.15		452.62		400.82		366.15						
C3	463.36	2.53	494.15		478.15		452.62		400.82		366.15		353.99		333.15		311.15
C4	228.60	2.29					433.15		400.82		366.15		355.15		333.15		
C5	193.34	1.82	495.15		478.15		452.62		389.15								
Cooling	115.368	2.62											355.15		333.15		311.15

Application of LP on the reduced diagram generates a network with 34 units and an area of 4342.38 m², some 5% above the minimum target area. This is the initial network for further evolution in the first route.

b) Second route.

To simplify the task ahead of applying LP, in a second route, as suggested by heuristics (satisfy the smallest heat load with 1 exchanger unit), a heater is imposed on a branch of cold stream C5 and the other branch of C5 is matched with a branch of hot stream H3. The remaining problem is processed as in the first route.

c) Third route.

In a third route, cold stream C5 is matched with a branch of hot stream H3, and a heater is imposed on a branch of cold stream C2, fitting into the grid diagram. The remaining problem is further processed as in the first route.

Obviously, inspection of the grid diagram might suggest other matches. Evolution of the networks enables cost reduction by elimination of heat exchanger units. In this phase, the imposed EMAT of 10 K is kept. The following techniques are applied for optimisation:

- introduction of non-isothermal splits,
- development by incremental evolution,
- distortion of the solution space,
- use of smart nodes.

Once the above techniques are exhausted, then swaps between HEX units in a same integration band are explored to remove EMAT constraints and, if successful, the optimisation techniques are repeated. Finally, split configurations and splits are analysed where they lead to EMAT constraints and, eventually, optimised.

The initial network of route 1 has a heater on cold stream C2 and a smaller heater on cold steam C5. After evolution, there is 1 heater left on cold stream C2.

Route 2 with a heater on cold stream C5 leads to a network with a quite similar structure. Differences between the two networks are:

- the location of the heater,
- the load distribution among the heat exchanger units,
- the split ratios.

Evolution in route 3 leads to the same network as in route 1 with the heater on cold stream C2.

Diverse types of splits as shown in Figure 16.3 were investigated for the first split in hot stream H1; related to the investment cost, the differences with the best split are less than 0.07% for route 1 and less than 0.009% for route 2.

Both networks fully satisfy the energy targets. The network with the heater on cold stream C5 has the lowest cost (13317.88 k$/year); the difference with the other network, however, is marginal (680 $/year). The 2 networks with 17 units and 10 splits are shown with a heater on cold stream C5 in Figure 16.4, respectively on cold stream C2 in Figure 16.5. In both networks, heat exchanger unit A15 could be replaced by a second cooler, in which case the cost would go up with a marginal 192 $/year.

After synthesising the networks for a heating load of 10.908 kW, these networks can be further developed into the threshold case with no heating; this leads to a single best solution with a total cost of 5955.09 k$/year. This network is shown in Figure 16.6.

All results are within less than 0.4% of target costs. They can be compared with published results in Table 16.4. Threshold networks have not been reported in literature.

Table 16.4	Heating	Cooling	Area	# units	# splits	Energy	Capital	Total cost	Heater on
DTMin 10 K	kW	kW	m^2	-	-	'000 $/y	'000 $/y	'000 $/y	
Faria et al.	151.39	254.85	3 067	11	1	99 309.25	296.78	99 606.03	C5
Kim et al.	151.39	254.85	3 322	12	1	99 309.25	322.01	99 631.26	C5
Nair et al.	42.681	146.14	5 008	13	12	31 961.00	458.29	32 419.29	C4
This study									
Targets	11.91	115.37	4 138	15	-	12 896.50	401.27	13 297.77	
Results	11.91	115.37	4 263	17	10	12 896.50	421.38	13 317.88	C5
	11.91	115.37	4 269	17	10	12 896.50	422.07	13 318.56	C2
DTMin 9.0385 K									
Targets	0.00	103.46	4 369	14	-	5 519.49	413.92	5 933.41	-
Results	0.00	103.46	4 511	16	12	5 519.49	435.61	5 955.09	-

The cost of the best network with an EMAT of 10 K is less than 14% of the cost of the network in [128] and 58.9 % lower than the cost of the best network published so far. With an EMAT of 9.0385 K, no heating is needed, and the cost can drop further with another 55%.

The initial network based on the original grid is not unique but depends upon the sequence of the streams as input for the LP application. A different sequence will generate a different initial network with the same area and area cost but with a different distribution of the loads on the heat exchanger units in the integration bands. With 144 possible permutations in the sequences, there are as many different initial networks, each of which could develop into a network, different from those presented here.

Figure 16.1

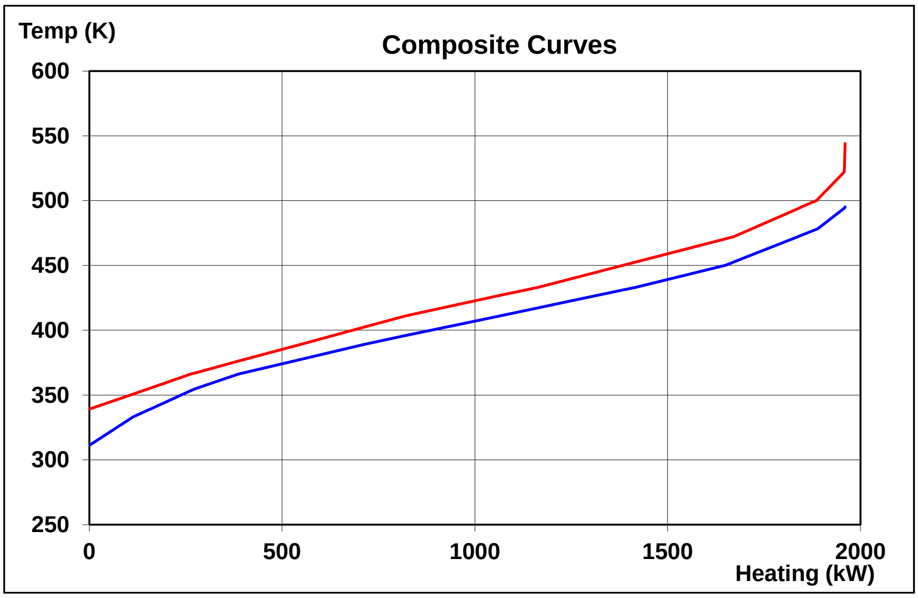


Figure 16.2

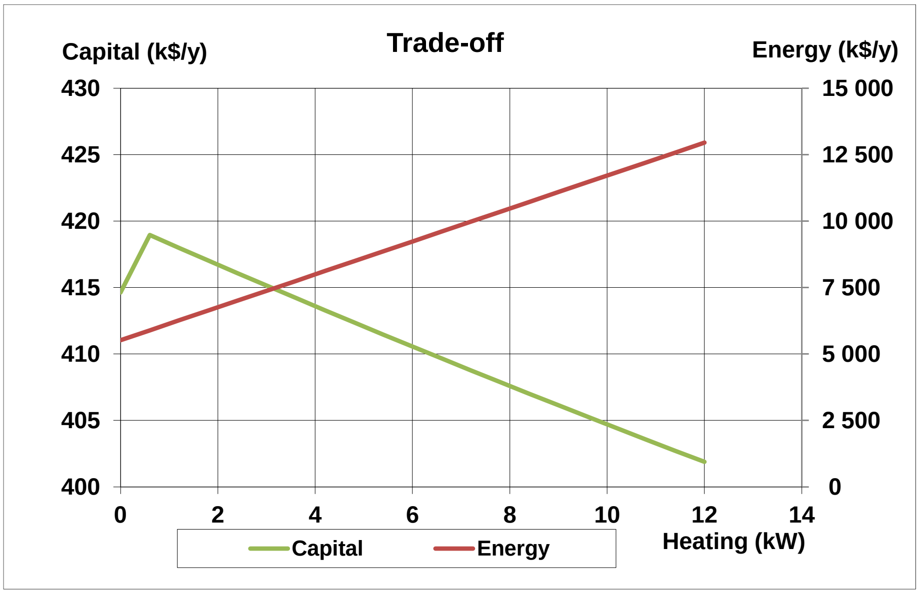
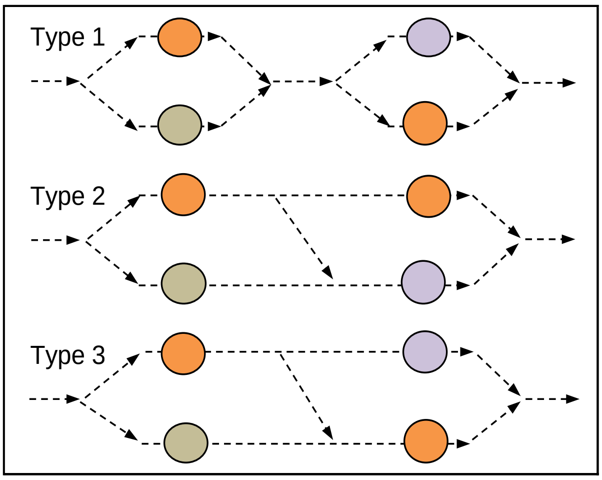


Figure 16.3



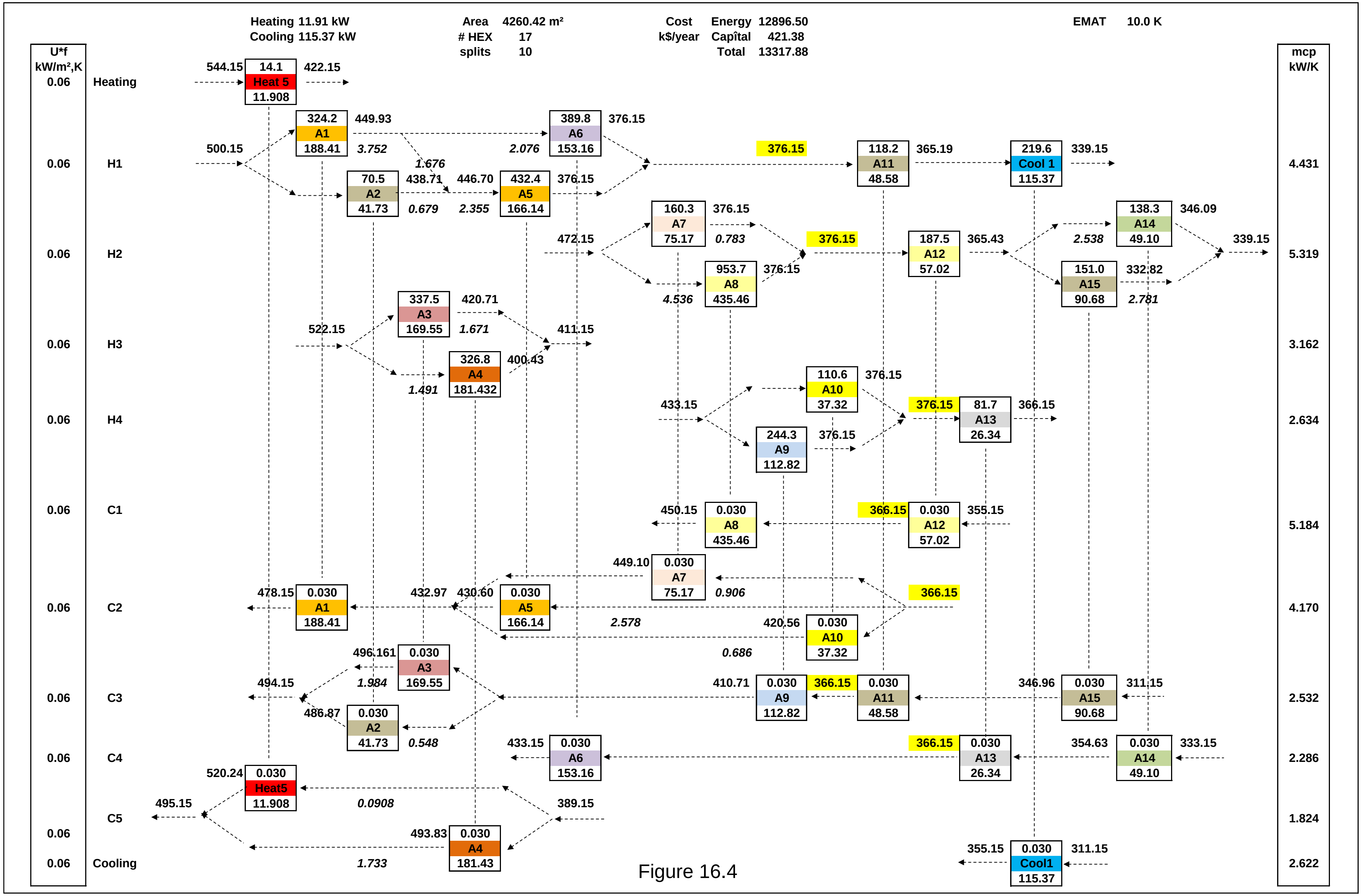

Heating 11.91 kW
Cooling 115.37 kW
Area 4260.42 m²
HEX 17
splits 10
Cost k$/year
Energy 12896.50
Capîtal 421.38
Total 13317.88
EMAT 10.0 K
U*f kW/m²,K
mcp kW/K
Heating
H1
H2
H3
H4
C1
C2
C3
C4
C5
Cooling
0.06
4.431
5.319
3.162
2.634
5.184
4.170
2.532
2.286
1.824
2.622
544.15
14.1
Heat 5
11.908
422.15
500.15
324.2
A1
188.41
449.93
3.752
389.8
A6
153.16
376.15
2.076
1.676
70.5
A2
41.73
438.71
446.70
0.679
2.355
432.4
A5
166.14
376.15
376.15
118.2
A11
48.58
365.19
219.6
Cool 1
115.37
339.15
160.3
A7
75.17
0.783
472.15
953.7
A8
435.46
4.536
376.15
187.5
A12
57.02
365.43
138.3
A14
49.10
346.09
2.538
151.0
A15
90.68
332.82
2.781
339.15
337.5
A3
169.55
420.71
1.671
522.15
411.15
326.8
A4
181.432
400.43
1.491
110.6
A10
37.32
376.15
433.15
244.3
A9
112.82
376.15
81.7
A13
26.34
366.15
450.15
0.030
A8
435.46
366.15
0.030
A12
57.02
355.15
449.10
0.030
A7
75.17
0.906
478.15
0.030
A1
188.41
432.97
430.60
0.030
A5
166.14
366.15
2.578
420.56
0.030
A10
37.32
0.686
496.161
0.030
A3
169.55
494.15
1.984
410.71
0.030
A9
112.82
366.15
0.030
A11
48.58
346.96
0.030
A15
90.68
311.15
486.87
0.030
A2
41.73
0.548
433.15
0.030
A6
153.16
366.15
0.030
A13
26.34
354.63
0.030
A14
49.10
333.15
520.24
0.030
Heat5
11.908
495.15
0.0908
389.15
493.83
0.030
A4
181.43
1.733
355.15
0.030
Cool1
115.37
311.15

Figure 16.4

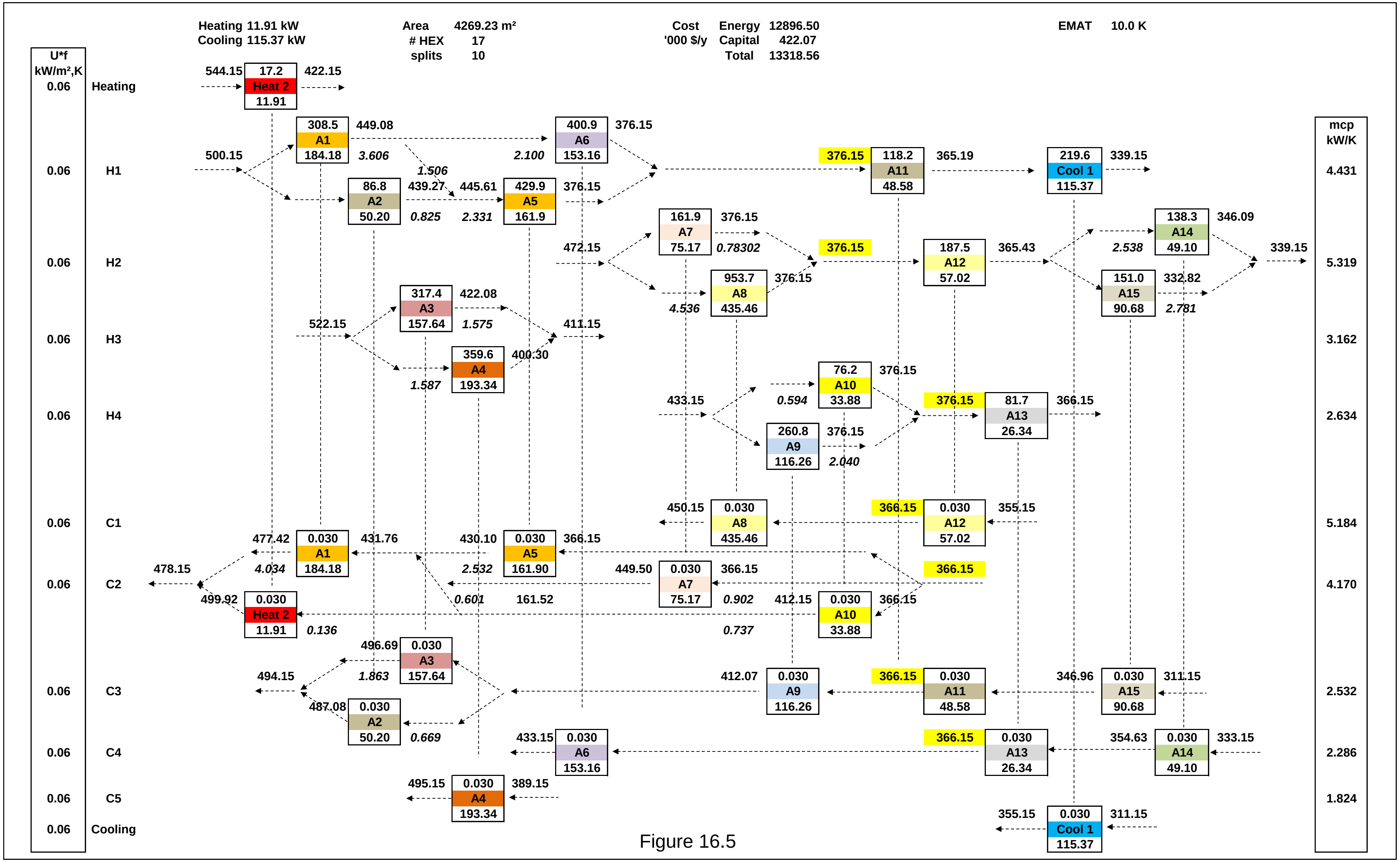

Heating 11.91 kW
Cooling 115.37 kW
Area 4269.23 m²
HEX 17
splits 10
Cost '000 $/y
Energy 12896.50
Capital 422.07
Total 13318.56
EMAT 10.0 K
U*f kW/m²,K
mcp kW/K
0.06 Heating
544.15 17.2 Heat 2 11.91 422.15
0.06 H1 500.15 4.431
308.5 A1 184.18 449.08 3.606
400.9 A6 153.16 376.15 2.100
1.506
86.8 A2 50.20 439.27 0.825
445.61 429.9 A5 161.9 2.331 376.15
376.15 118.2 A11 48.58 365.19
219.6 Cool 1 115.37 339.15
0.06 H2 472.15 5.319
161.9 A7 75.17 376.15 0.78302
953.7 A8 435.46 4.536 376.15
376.15 187.5 A12 57.02 365.43
138.3 A14 49.10 346.09 2.538
151.0 A15 90.68 332.82 2.781
339.15
0.06 H3 522.15 3.162
317.4 A3 157.64 422.08 1.575
359.6 A4 193.34 400.30 1.587
411.15
0.06 H4 433.15 2.634
76.2 A10 33.88 376.15 0.594
260.8 A9 116.26 376.15 2.040
376.15 81.7 A13 26.34 366.15
0.06 C1 5.184
450.15 0.030 A8 435.46
366.15 0.030 A12 57.02 355.15
0.06 C2 478.15 4.170
477.42 0.030 A1 184.18 431.76 4.034
430.10 0.030 A5 161.90 366.15 2.532
449.50 0.030 A7 75.17 366.15 0.902
366.15
0.601 161.52
499.92 0.030 Heat 2 11.91 0.136
412.15 0.030 A10 33.88 366.15 0.737
0.06 C3 494.15 2.532
496.69 0.030 A3 157.64 1.863
487.08 0.030 A2 50.20 0.669
412.07 0.030 A9 116.26
366.15 0.030 A11 48.58
346.96 0.030 A15 90.68 311.15
0.06 C4 2.286
433.15 0.030 A6 153.16
366.15 0.030 A13 26.34
354.63 0.030 A14 49.10 333.15
0.06 C5 1.824
495.15 0.030 A4 193.34 389.15
0.06 Cooling
355.15 0.030 Cool 1 115.37 311.15

Figure 16.5

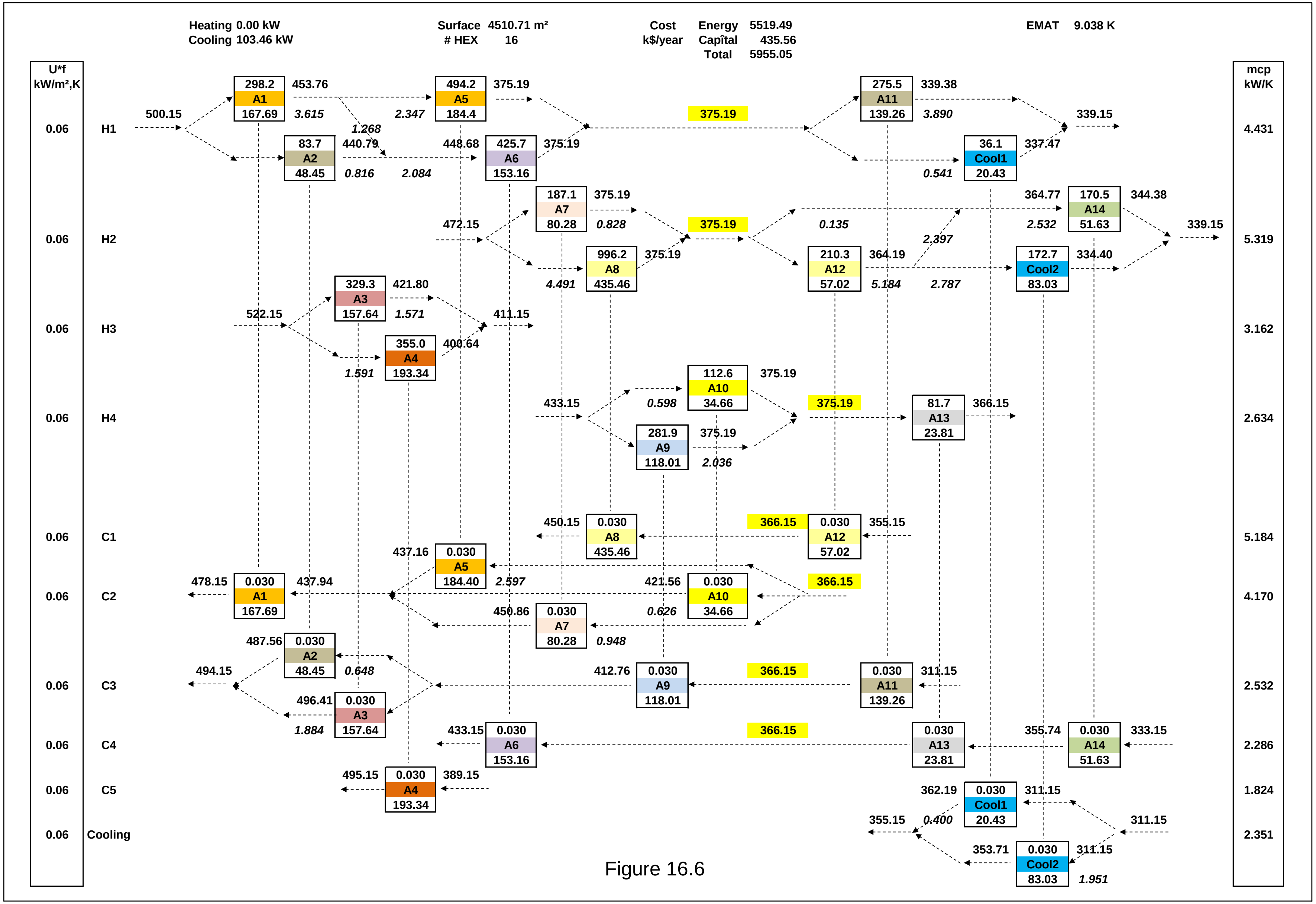

Heating 0.00 kW
Cooling 103.46 kW
Surface 4510.71 m²
HEX 16
Cost k$/year
Energy 5519.49
Capital 435.56
Total 5955.05
EMAT 9.038 K
U*f kW/m²,K
mcp kW/K
H1
H2
H3
H4
C1
C2
C3
C4
C5
Cooling
0.06
4.431
5.319
3.162
2.634
5.184
4.170
2.532
2.286
1.824
2.351
500.15
522.15
433.15
472.15
339.15
411.15
298.2
A1
167.69
453.76
3.615
83.7
A2
48.45
440.79
0.816
329.3
A3
157.64
421.80
1.571
355.0
A4
193.34
400.64
1.591
494.2
A5
184.4
375.19
2.347
1.268
425.7
A6
153.16
448.68
2.084
187.1
A7
80.28
0.828
996.2
A8
435.46
4.491
281.9
A9
118.01
2.036
112.6
A10
34.66
0.598
275.5
A11
139.26
339.38
3.890
210.3
A12
57.02
364.19
5.184
81.7
A13
23.81
366.15
170.5
A14
51.63
344.38
364.77
2.532
2.397
2.787
0.135
36.1
Cool1
20.43
337.47
0.541
172.7
Cool2
83.03
334.40
0.030
450.15
355.15
437.16
478.15
437.94
2.597
421.56
450.86
0.626
0.948
487.56
494.15
0.648
496.41
1.884
412.76
311.15
433.15
355.74
333.15
495.15
389.15
362.19
355.15
0.400
353.71
1.951

Figure 16.6

17 Literature

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