Benchmark solutions for small heat exchanger networks.

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

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This note is a summary of benchmark solutions for 12 small heat exchanger networks. The data sets have 2 hot streams, 2 cold steams, one hot and one cold utility.

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1. Example from Shenoy

Example 1 is from Shenoy [1.1]. The data set is given in Table 1.1. Energy consumption in the table corresponds with an overall DTMin of 13 K. Composite curves are shown in Figure 1.1.

The annual cost factor A_f was calculated according to the formula $A_f = (1+i)^n/n$ whereas i is an interest rate (10%) and n is the project life time (5 years). It should be understood that this annual cost factor is arbitrary and does not correspond to the annuity of the investment required to generate a Net Present Value equal to that investment. Since, however, said cost data have been used in the scientific publications, they have been withheld for further comparison.

As shown in Figure 1.2, trade-off in classic pinch analysis gives a total cost target of 239,450 $/year for a heating load of 360 kW and a network with 6 units. The cost target for a single system with 5 units, also for a heating load of 360 kW, is 226,111 $/year.

The results developed by Shenoy are shown in Table 1.2, which has been completed with results obtained after further optimisation of the networks by incremental evolution and after distortion of the solution space. Cost figures with coloured background are duplicates.

A network with minimum cost can be obtained with a smart tick-off procedure respecting the following rules:

- Rule 1: satisfy smallest loads with one unit
- Rule 2: match a stream stretching over the pinch with a (branch of a) counterpart also stretching over the pinch
- Rule 3: no heating below the pinch, no cooling above the pinch, no match across the pinch

The procedure leads to the following matches:

- C2 on a branch H2b of H2 (rules 1 and 3)
- H1 on a branch C1a of C1 (rules 1 and 2)
- Cooler on the cold side of branch H2a
- Heater on hot side branch C1b (rule 3)
- Fill in the remaining match H2a – C1b.

The result is a network with 5 units and 2 splits with a cost of 230,549 $/year, evolving to 227,544 $/year after further optimisation by incremental evolution on the flowsheet (Figure 1.3). Relocation of the Cooler from branch H2a to branch H2b and further optimisation leads to the optimum network of Figure 1.4 with a cost of 226,721 $/year, which is within 0.27% of the target.

An optimum network without stream splits can be derived from networks with splits, provided the cooler is on hot stream H1 and the heating is increased to above 480 kW. That network has 5 units for a cost of 241,922 $ (Figure 1.5).

Several alternative networks can be developed by using simple automated procedures. The grid from the analysis contains 7 bands (superstructures) which can be reduced to 4. Allocating the cooler to hot stream H1, alternatively H2 generates simplified grids as shown in Table 1.3. Application of LP to these grids results into the placement of heat exchanger units as shown in Table 1.4. Cases A and B require the same area but will have different costs; also C and D will have the same area but different costs. Further optimisation of the flowsheets by incremental evolution gives the results of Table 1.5.

Reducing the grid to 3 bands as shown in Table 1.6 and applying LP results into the placement of heat exchanger units as shown in Table 1.7. Further optimisation of the flowsheets by incremental evolution gives the results of Table 1.8. Also the network with minimum cost can be generated automatically by using this procedure.

References:

[1.1] Shenoy, U. V., 1995, Heat Exchanger Network Synthesis: Process Optimization by Energy and Resource Analysis (Gulf Publishing Co., Houston, TX, USA) .

[1.2] Rezae, E. Shafiei, S., An NLP Approach for Evolution of Heat Exchanger Networks Designed by Pinch Technology, Iranian Journal of Chemical Engineering Vol. 5, No. 1 (Winter), 2008, IAChE

Table 1.1

Tsupply °C	Ttarget °C	Heat kW	DT-Shift K	U*f kW/K,m²	Descript -
175	45	1300	6.5	0.2	H1
125	65	2400	6.5	0.2	H2
20	155	2700	6.5	0.2	C1
40	112	1080	6.5	0.2	C2
180	179	360		0.2	Heating
15	25	280		0.2	Cooling

Cost data

Heating : 120 $/kW,year Cooling : 10 $/kW,year

Area Cost ($) = 30000 + 750 x Area$^{0.81}$ Annual cost factor = 0.3221

Annual Area Cost ($/year) = 9663 + 241.575 x Area$^{0.81}$

Table 1.2

Results Shenoy	Reported				Optimised			
	Heating	# units	# splits	Cost	Heating	# units	# splits	Cost
Case	kW	-	-	$/year	kW	-	-	$/year
S1	360.0	6	1	245,828	371.9	6	1	242,336
Push up / pull down °1)					565.9	5	1	239,796
S2	360.0	6	1	248,238	388.2	6	1	241,849
Push up / pull down °1)					565.9	5	1	239,796
S3	360.0	6	2	240,025	353.3	6	2	238,173
Pull down					392.8	5	2	228,602
S4	360.0	6	2	261,423	384.7	6	2	251,218
Pull down					513.0	5	0	244,616

°1) network identical with the network reported by Rezaei

Table 1.3

4 bands, Cooler on H1				**area**	**#HEX**	**AreaCost**			
			Design	1658.86	6	190.33			
Tsupply	Ttarget	Heat	Descript.	mcp					
°C	°C	kW	-	kW/K	Bands				
					1	2	3	4	
180	179	360	Heating	360	180.0	179.0			
175	45	1300	H1	10		175.0	125.0	73.0	45.0
125	65	2400	H2	40			125.0	65.0	
20	155	2700	C1	20	155.0	137.0	112.0	20.0	
40	112	1080	C2	15			112.0	40.0	
15	25	280	Cooling	28				25.0	15.0

4 bands, Cooler on H2				**area**	**#HEX**	**AreaCost**			
			Design	1699.80	6	194.04			
Tsupply	Ttarget	Heat	Descript.	mcp					
°C	°C	kW	-	kW/K	Bands				
					1	2	3	4	
180	179	360	Heating	360	180.0	179.0			
175	45	1300	H1	10		175.0	125.0	45.0	
125	65	2400	H2	40			125.0	72.0	65.0
20	155	2700	C1	20	155.0	137.0	112.0	20.0	
40	112	1080	C2	15			112.0	40.0	
15	25	280	Cooling	28				25.0	15.0

Table 1.4

LP 4 bands - Cooling on H1

A

Band		Heating	H1	H2
1	C1	360.0		
2	C1		500.0	
3	C1			1840.0
	C2		520.0	560.0
4	Cooling		280.0	

B

Band		Heating	H1	H2
1	C1	360.0		
2	C1		500.0	
3	C1		520.0	1320.0
	C2			1080.0
4	Cooling		280.0	

LP 4 bands - Cooling on H2

C

Band		Heating	H1	H2
1	C1	360.0		
2	C1		500.0	
3	C1		800.0	1040.0
	C2			1080.0
4	Cooling			280.0

D

Band		Heating	H1	H2
1	C1	360.0		
2	C1		500.0	
3	C1			1840.0
	C2		800.0	280.0
4	Cooling			280.0

Table 1.5

Results LP 4 bands	Initial network				Optimised			
	Heating	# units	# splits	Cost	Heating	# units	# splits	Cost
Case	kW	-	-	$/year	kW	-	-	$/year
A	360.0	6	2	236,319	341.7	6	2	234,344
B	360.0	6	2	237,897	335.5	6	2	236,423
Pull down					421.7	5	2	239,066
Push up / pull down					565.9	5	1	239,796

Cases C and D are identical with cases S3 and S4

Table 1.6

3 bands				**area**	**#HEX**	**AreaCost**		
			Design	1708.54	8	217.20		
Tsupply °C	Ttarget °C	Heat kW	Descript. -	mcp kW/K				
					1	2	3	
180	179	360	Heating	360	180.0	179.0		
175	45	1300	H1	10	175.0	125.0	74.6	45.0
125	65	2400	H2	40		125.0	74.6	65.0
20	155	2700	C1	20	155.0	112.0	40.0	20.0
40	112	1080	C2	15		112.0	40.0	
15	25	280	Cooling	28			25.0	15.0

Table 1.7

LP 3 bands - Cooling on H1

E

Band		Heating	H1	H2
1	C1	360	500	
2	C1			1440
	C2		504	576
3	C1		16	384
	Cooling		280	

F

Band		Heating	H1	H2
1	C1	360	500	
2	C1		504	936
	C2			1080
3			16	384
	Cooling		280	

LP 3 bands - Cooling on H2

G

Band		Heating	H1	H2
1	C1	360	500	
2	C1			1440
	C1		504	576
3	C2		296	104
	Cooling			280

H

Band		Heating	H1	H2
1	C1	360	500	
2	C1		504	936
	C1			1080
3	C2		296	104
	Cooling			280

Table 1.8

Results LP 3 bands	Initial network				Optimised			
	Heating	# units	# splits	Cost	Heating	# units	# splits	Cost
Case	kW	-	-	$/year	kW	-	-	$/year
E	360.0	8	5	263,184	348.8	6	3	237,130
Push up					732.1	5	2	260,864
F simple node	360.0	8	5	264,174	335.0	6	3	239,466
Pull down					421.7	5	2	239,066
F Smart node	360.0	8	5	264,174	335.0	6	3	239,466
Pull down					419.0	5	2	236,948
Push up / pull down					398.5	5	3	235,100
G simple & smart node	360.0	8	5	264,520	346.3	7	3	250,503
Pull down					398.0	6	3	253,046
Further pull down					513.0	5	1	245,630
H simple node	360.0	8	5	265,509	392.3	5	2	228,602
H Smart node a °1)					384.7	5	2	226,721
H Smart node b °2)					383.8	5	2	226,779

°1) 2 independent variables in band 2

°2) 1 independent variable in band 2; developes into variant a after push up / pull down.

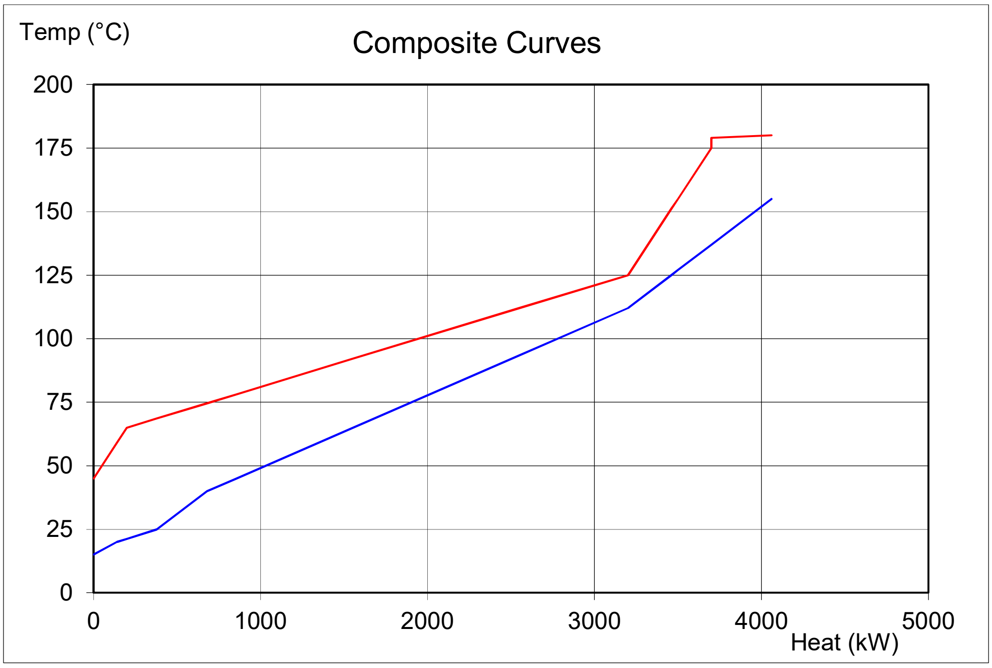


Figure 1.1

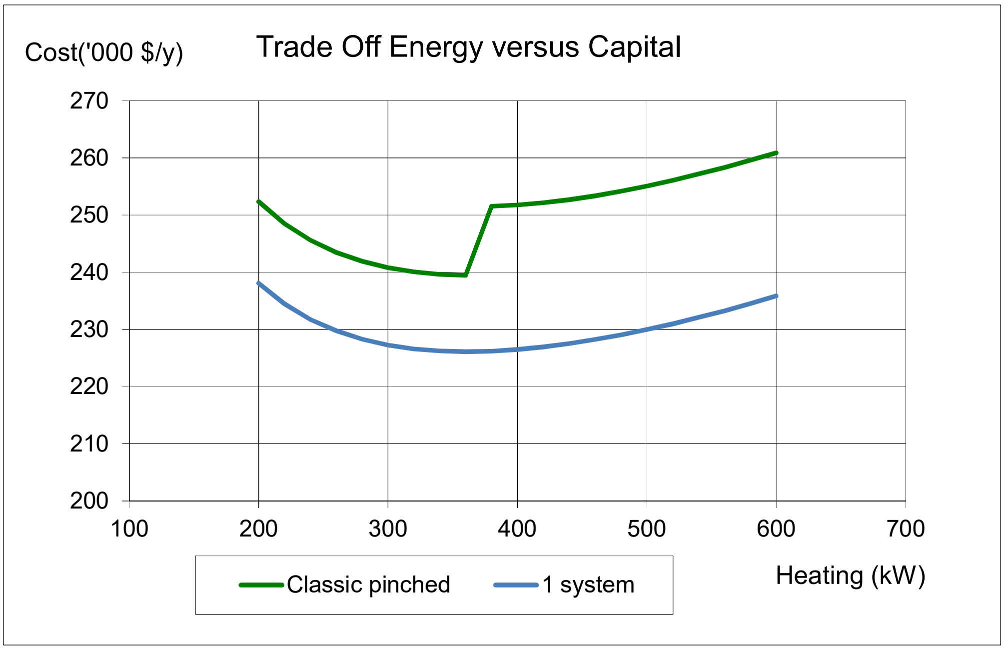


Figure 1.2

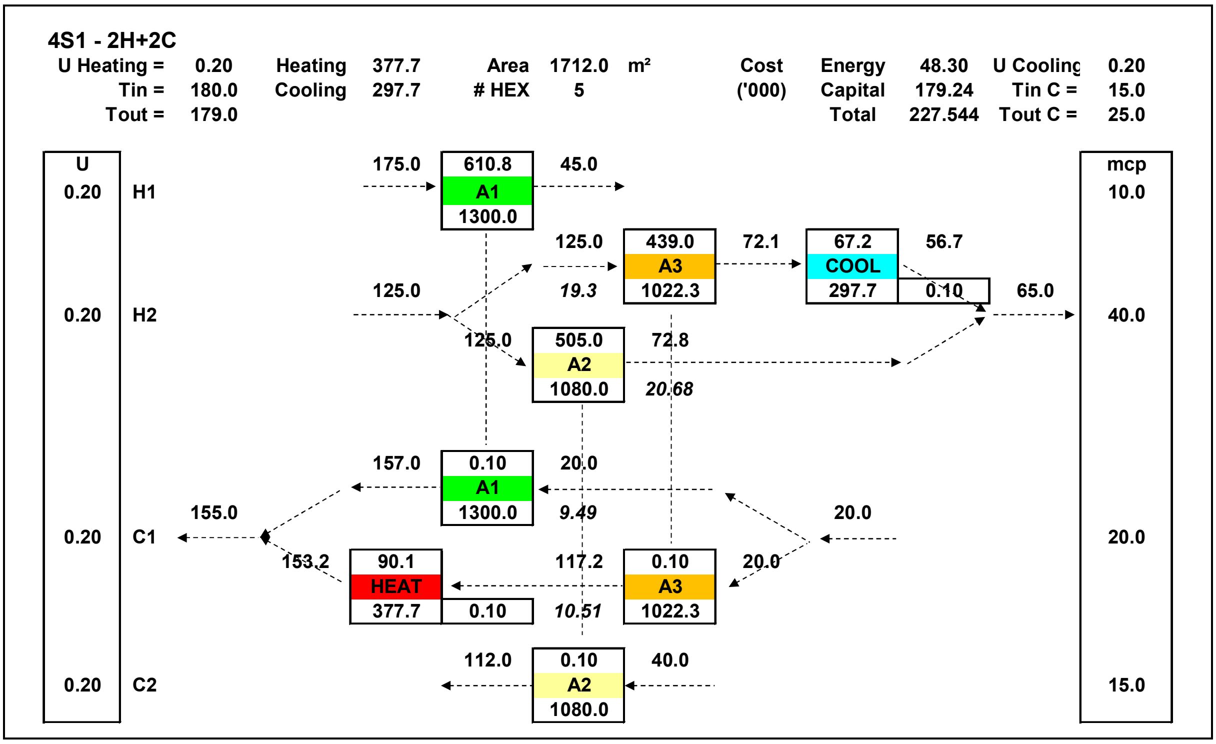


Figure 1.3

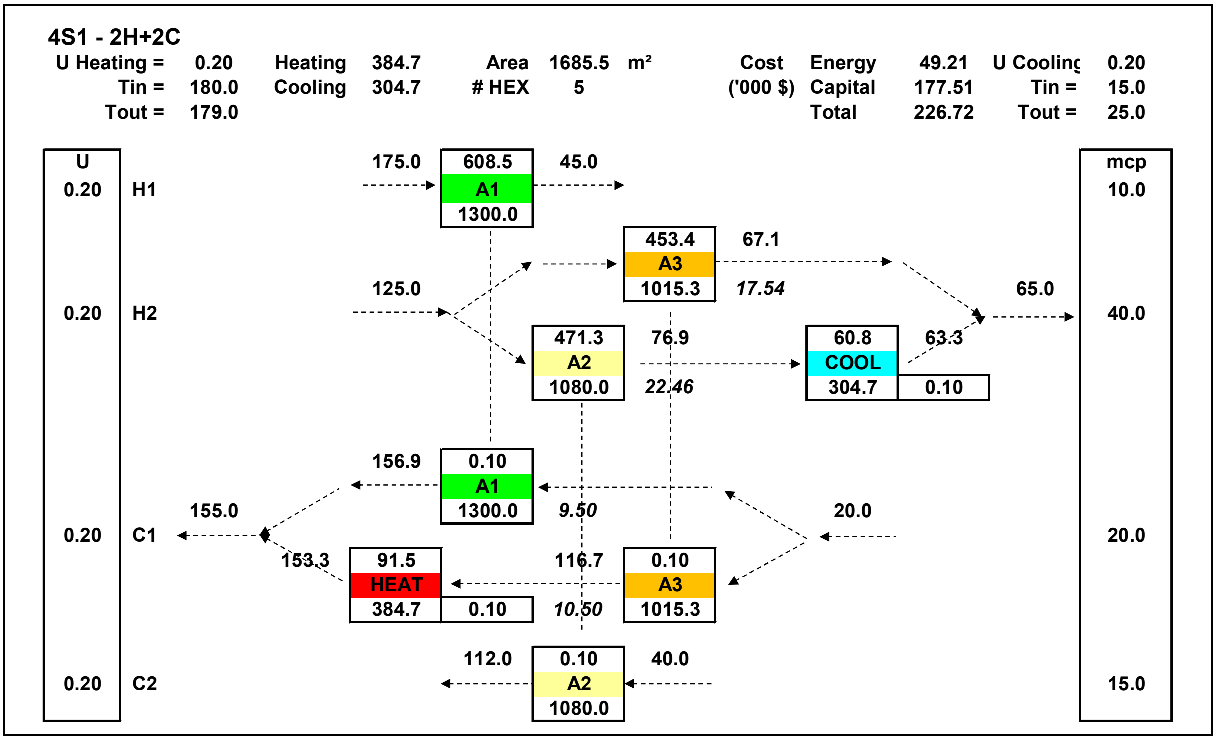


Figure 1.4

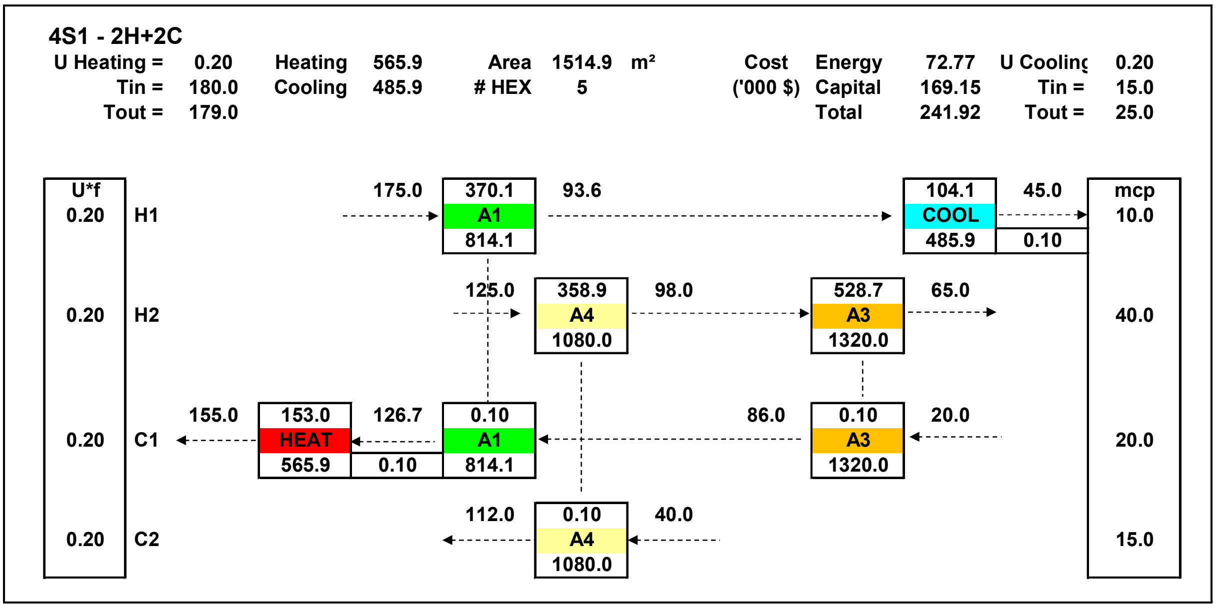

4S1 - 2H+2C
U Heating = 0.20
Tin = 180.0
Tout = 179.0
Heating 565.9
Cooling 485.9
Area 1514.9 m²
HEX 5
Cost ('000 $)
Energy 72.77
Capital 169.15
Total 241.92
U Cooling 0.20
Tin = 15.0
Tout = 25.0
U*f
0.20
H1
175.0
370.1
A1
814.1
93.6
104.1
COOL
485.9
45.0
0.10
mcp
10.0
0.20
H2
125.0
358.9
A4
1080.0
98.0
528.7
A3
1320.0
65.0
40.0
0.20
C1
155.0
153.0
HEAT
565.9
126.7
0.10
0.10
A1
814.1
86.0
0.10
A3
1320.0
20.0
20.0
0.20
C2
112.0
0.10
A4
1080.0
40.0
15.0

Figure 1.5

2. Example from Shenoy modified by Frausto-Fernandez

The example from Shenoy was modified by Frausto-Hernàndez [2.1] and then also treated by Ravagnani et al. in 2005 using Particle Swarm Optimization [2.2] and by Fieg et al. in 2009 using a hybrid genetic algorithm combined with a simulated annealing algorithm, local optimizing strategy, structure control strategy and other [2.3].

Modified heat transfer values and cost data as shown in Table 2.1 with Composite Curves as shown in Figure 2.1. The overall DeltaT of 5K and the corresponding heating and cooling loads result from the trade-off calculations as shown in Figure 2.2 using classic pinch analysis (2 systems); these results are identical with those obtained by Ravagnani.

Table 2.2 shows optimum DT-shift values obtained by crisscross optimisation in order to achieve minimum surface area. The targeted heating load is 185 kW, which is the same as for one system without crisscross optimisation. Further initial designs will be based on a heating load of 185 kW.

The network with lowest cost of 108,072 $/year (Figure 2.6) results from a grid after crisscross optimisation, applying LP on that grid and incremental evolution including non-isothermal splits. The network without split with lowest cost of 123,742 $/year (Figure 2.5) results from a grid without crisscross optimisation, applying LP on that grid, incremental evolution, distortion of the solution space and further incremental evolution. The results are summarized in Table 2.3.

References

[2.1] S. Frausto-Hernández, V. Rico-Ramírez, A. Jiménez-Gutiérrez, et al.; MINLP synthesis of heat exchanger networks considering pressure drop effects, Computers and Chemical Engineering 27 (2003) 1143–1152.

[2.2] Ravagnani, M. A. S. S., Silva, A. P., Arroyo, P. A., Constantino, A. A. (2005); Heat exchanger network synthesis and optimisation using genetic algorithm. Applied Thermal Engineering, 25, 1003–1017.

[2.3] Xing Luo, Qing-Yun Wen, Georg Fieg, A hybrid genetic algorithm for synthesis of heat exchanger networks, Computers and Chemical Engineering 33 (2009) 1169–1181

Table 2.1

Tsupply	Ttarget	Heat	DT-Shift	U*f	Descript
°C	°C	kW	K	kW/K,m²	-
175	45	1300	2.5	2.615	H1
125	65	2400	2.5	1.333	H2
20	155	2700	2.5	0.917	C1
40	112	1080	2.5	0.166	C2
180	179	200		5.000	Heating
15	25	120		2.500	Cooling

Cost data

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

Area Cost ($/year) = 1200 x Area$^{0.57}$

Table 2.2

Tsupply °C	Ttarget °C	Heat kW	DT-Shift K	U*f kW/K,m^2	Descript -
175	45	1300	0.0	2.615	H1
125	65	2400	1.0	1.333	H2
20	155	2700	0.0	0.917	C1
40	112	1080	8.0	0.166	C2
180	179	185		5.000	Heating
15	25	105		2.500	Cooling

Table 2.3

	Heating kW	Area m^2	Cost $/year	Units #	Splits #	Network
Without crisscross optimisation						
Analysis	185.0	671.2	119,661	5	-	
Initial design (8 bands - LP)	185.0	671.2	133,247	15	6	-
After incremental evolution	183.3	654.6	114,179	7	2	Fig.2.3
After distortion of solution space	213.5	660.0	113,985	6	2	Fig.2.4
After unwinding splits	324.0	572.2	123,743	6	0	Fig.2.5
With crisscross optimisation						
Analysis	185.0	637.8	116,548	5	-	
Initial design (8 bands - LP)	185.0	634.7	121,444	15	6	-
After incremental evolution	184.4	644.0	108,072	6	2	Fig.2.6
After unwinding splits	437.0	512.7	127,646	6	0	Fig.2.7

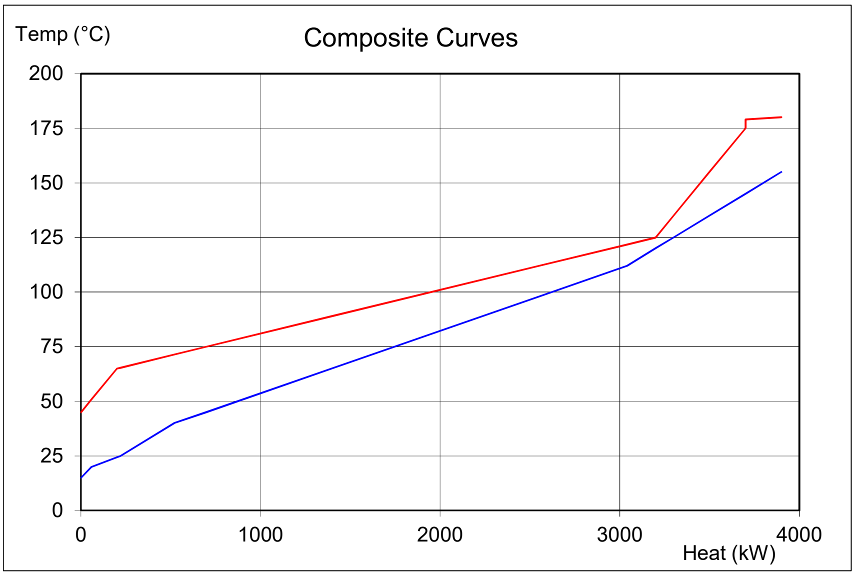


Figure 2.1

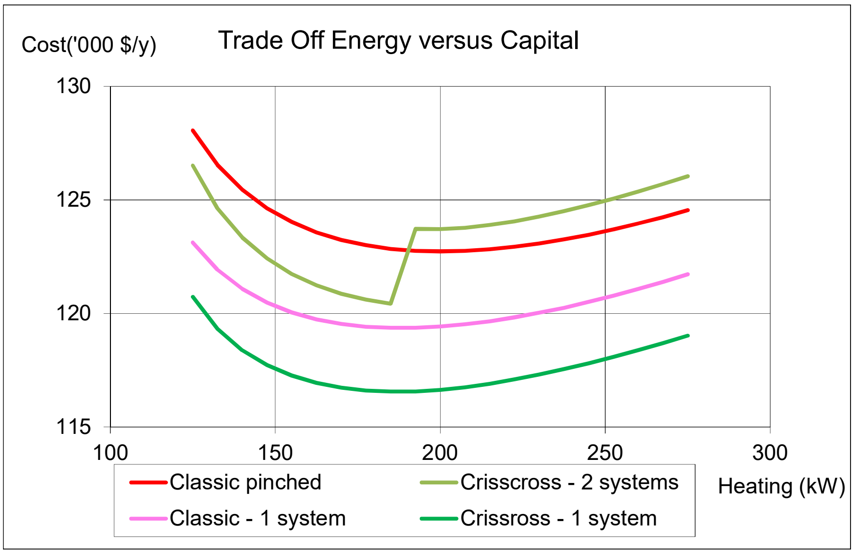


Figure 2.2

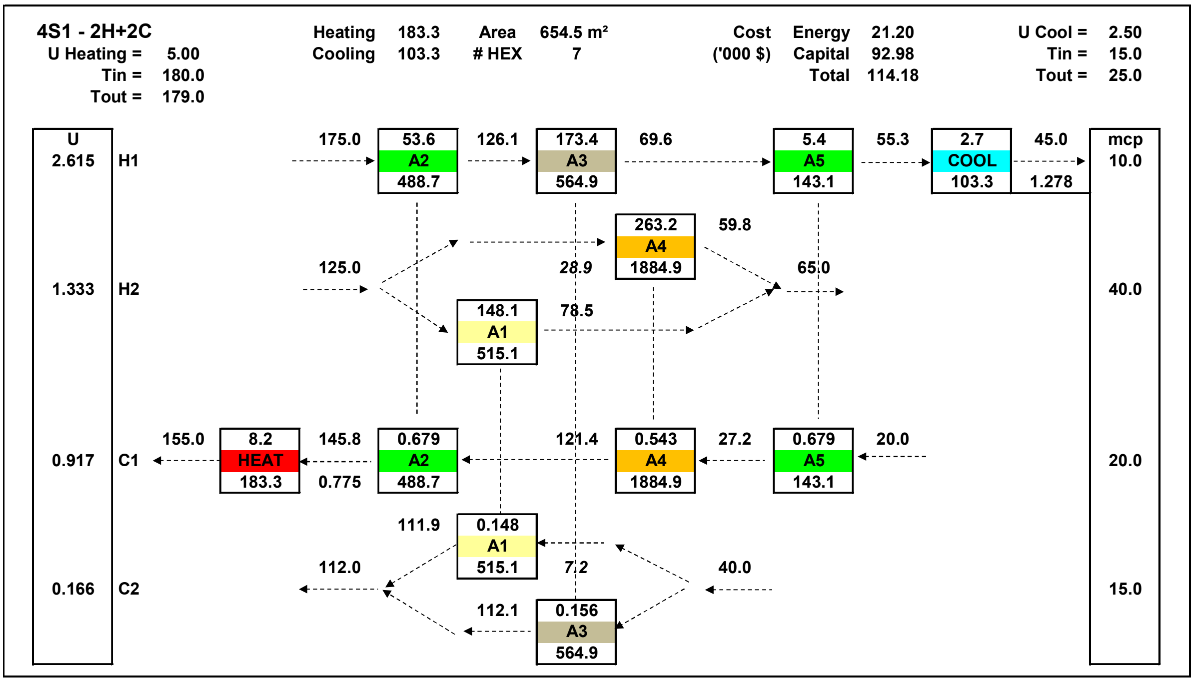


Figure 2.3

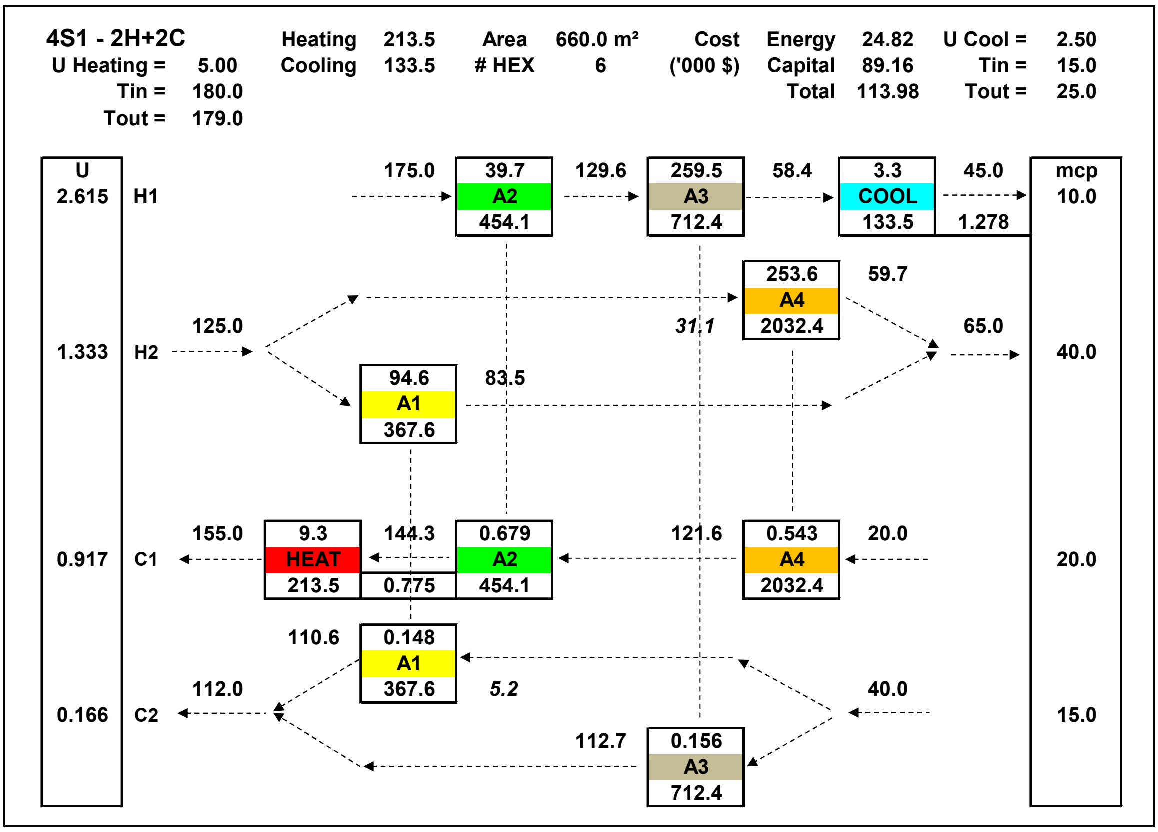


Figure 2.4

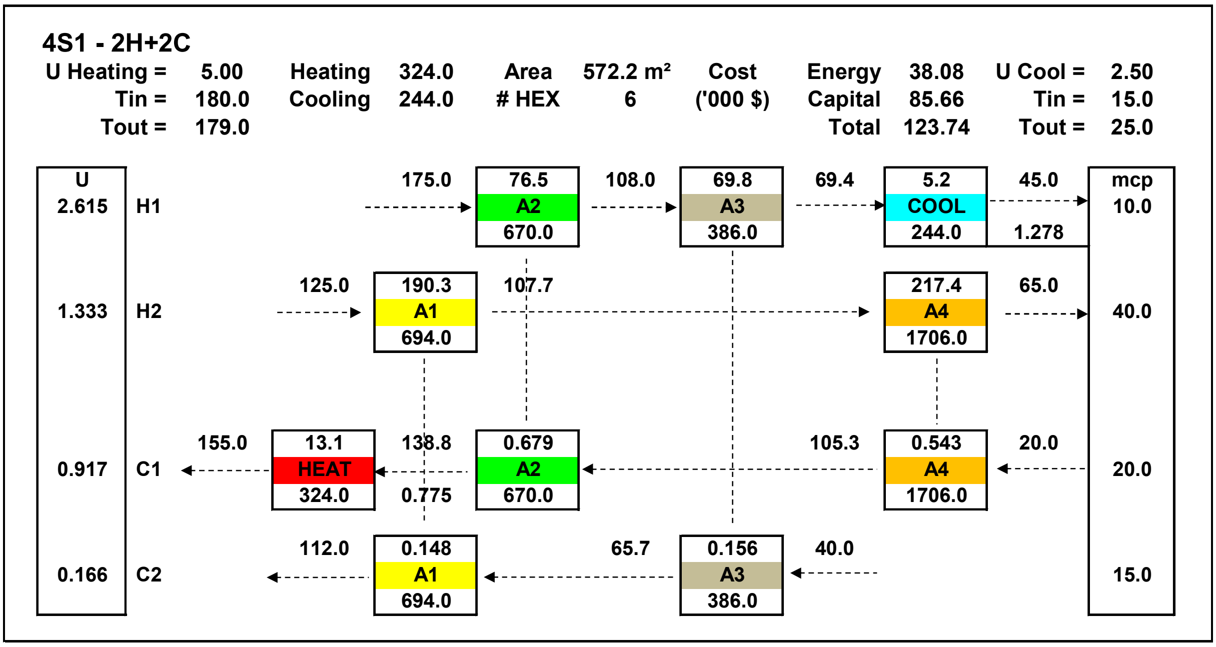


Figure 2.5

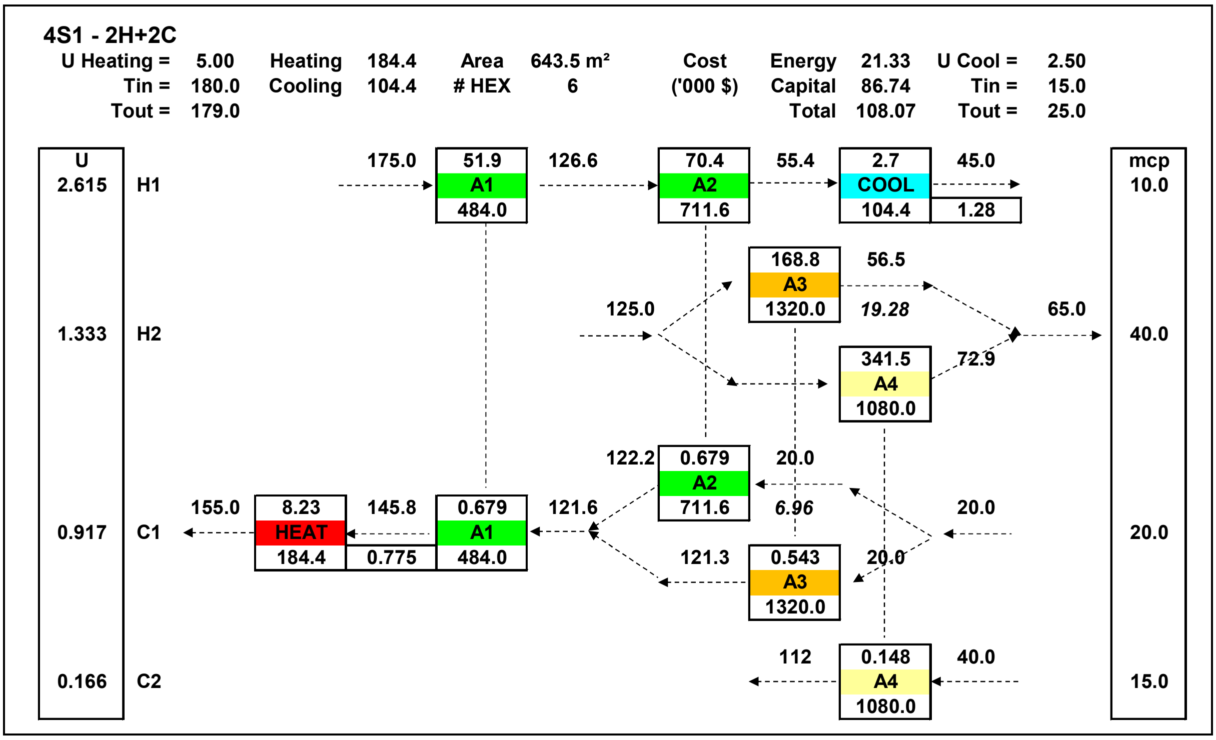


Figure 2.6

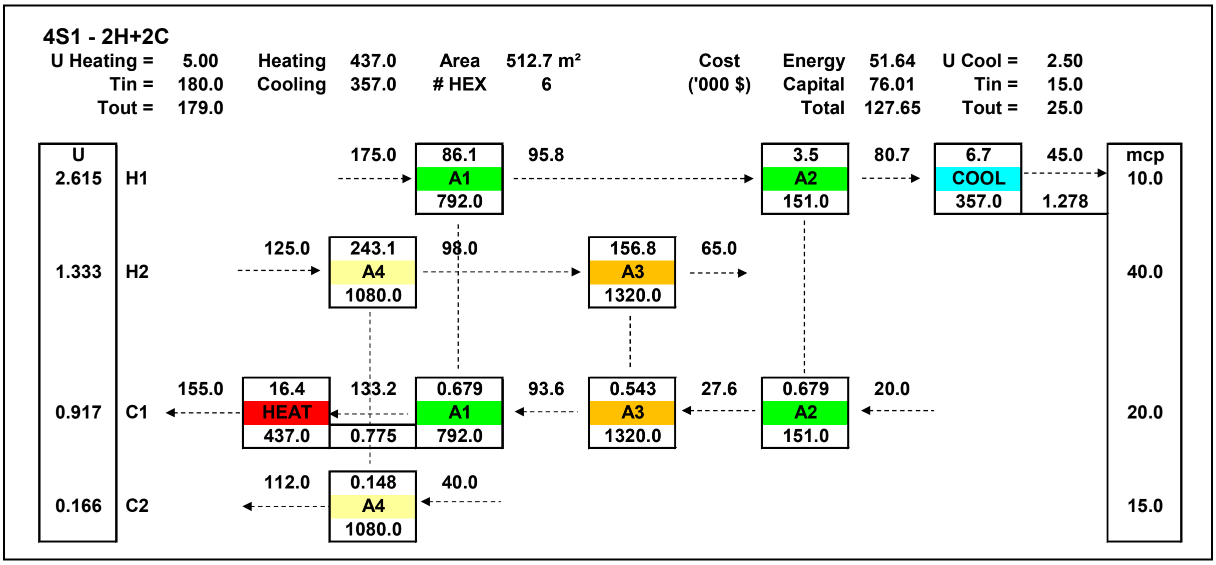


Figure 2.7

3. Example from Adjiman

Example 3 is from Adjiman [3.1]; it also has been studied by Faria et al. [3.2]. The data set is given in Table 3.1. Composite Curves are shown in Figure 3.1. Utility heat loads in the table correspond with the heating load for minimum cost in the trade-off curves of Figure 3.2 in classic pinch analysis (2 systems) as well as for a network with 1 system. Target cost for a network with 1 system is 145,575 $/year.

Design rules of pinch analysis lead to a network with 6 units and an annual cost of 157,219 $, which after incremental evolution drops to 154,853 $ (Figure 3.3). 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, however, enables to get out of the 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 3.4).

References:

[3.1] C.S. Adjiman, I.P. Androulakis, and C.A. Floudas, Global Optimization of Mixed-Integer Nonlinear Problems, Process Systems Engineering, AIChE Journal Sept. 2000 Vol. 46, N° 9, pages 1769- 1797.

[3.2] Faria D. and M. Bagajewicz, Global Optimization of Nonconvex MINLP Problems by Domain and Image Partitioning: Applications to Heat Exchanger Networks, University of Oklahoma, USA

[3.3] Lin, B. and Miller, D. C., “Solving heat exchanger network synthesis problems with tabu search,” Computers and Chemical Engineering, 28, 1451-1464 (2003).

[3.4] E. Rezaei E., Shafiei S., An Efficient Coupled Genetic Algorithm-NLP Method for Heat Exchanger Network Synthesis, Iranian Journal of Chemical Engineering Vol. 5, No. 1 (Winter), 2008, IAChE

Table 3.1

Tsupply K	Ttarget K	Heat kW	DT-Shift K	U kW/K,m²	Descript -
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 $/kW,year
Area Cost ($/year): 5500 + 150 x Area

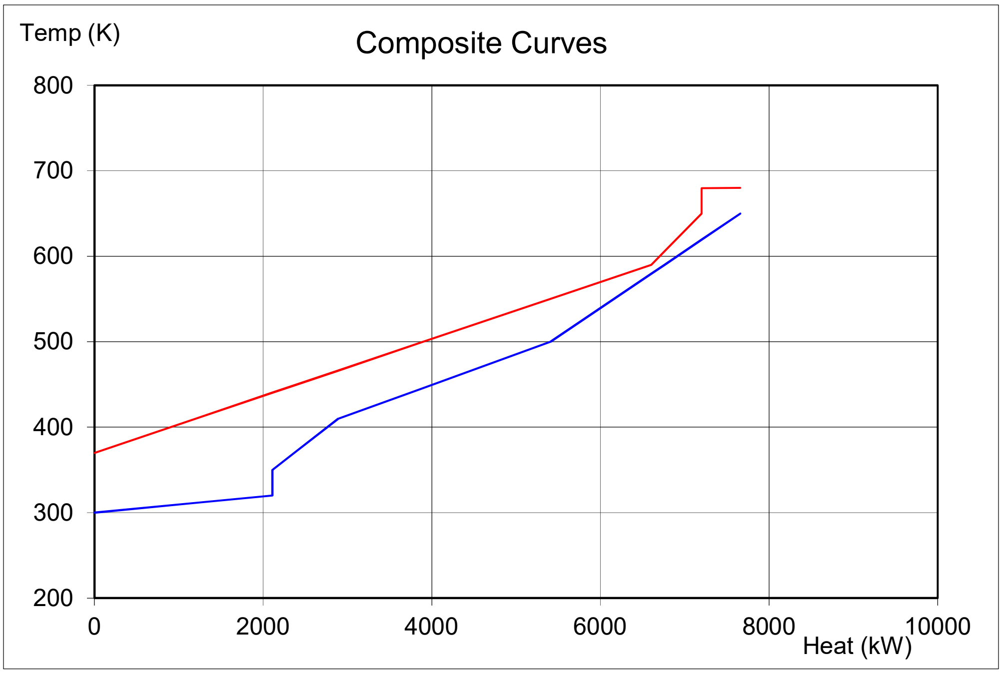


Figure 3.1

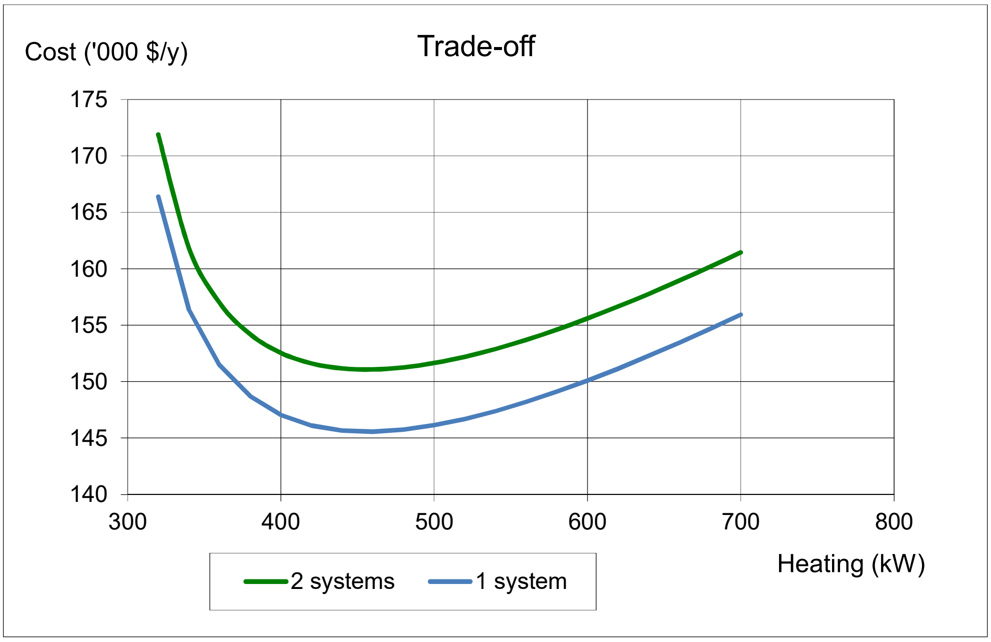


Figure 3.2

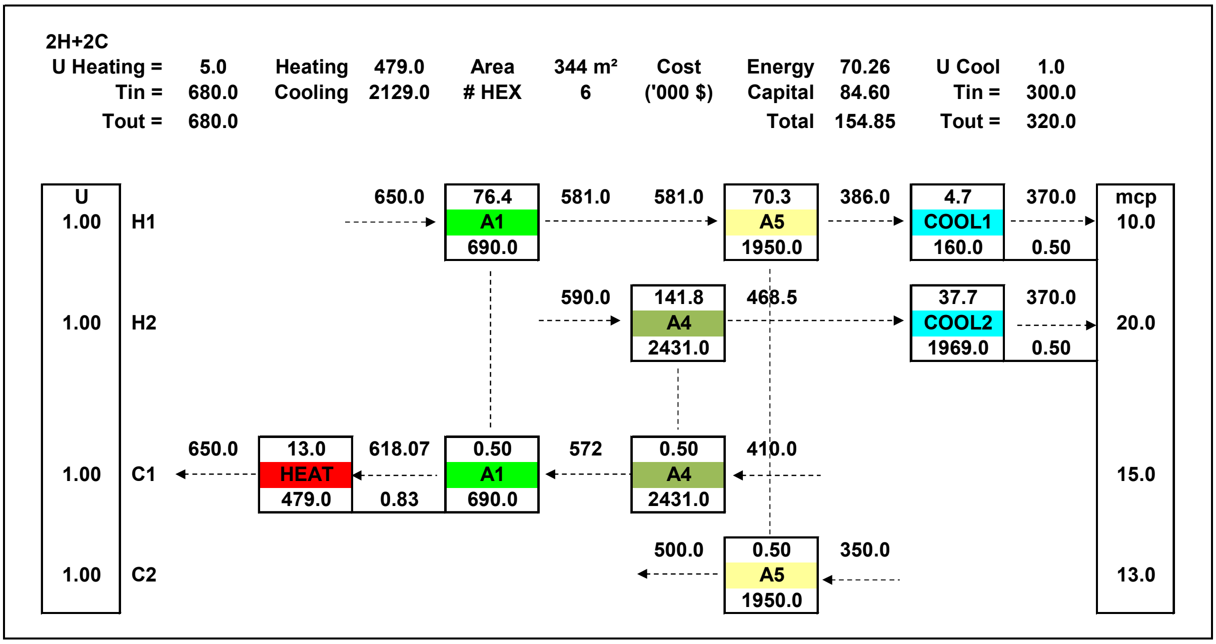


Figure 3.3

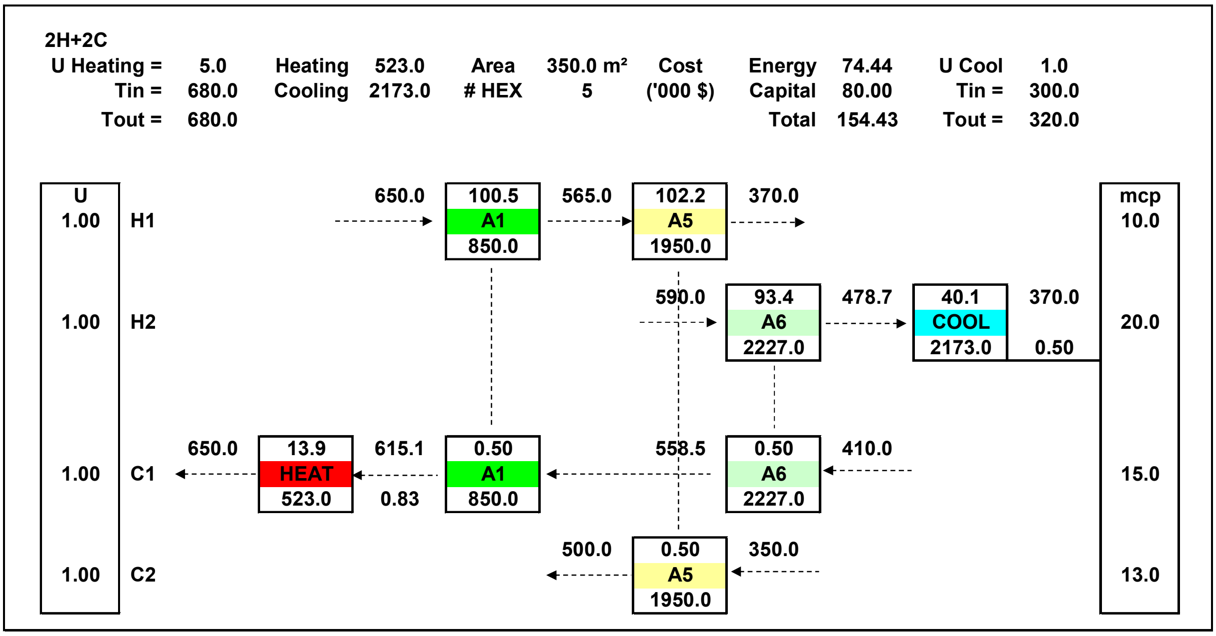


Figure 3.4

4. Example from Trivedi et al.

Example 4, from Trivedi et al. [4.1] has also been studied by Jezowski et al. [4.2] and by Rezaei et al. [4.3]. The data set is given in Table 4.1. Utility heat loads in the table correspond with the overall DTMin of 20 K. Composite Curves are shown in Figure 4.1.

With reference to the trade-off curves of Figure 4.2, a more appropriate heating load for minimum cost would be 5000 kW with a targeted cost of 1,038,168 $/year for a network with 5 units.

Application of pinch design rules (tick-off) leads to a network with 7 units and a cost of 1,081,226 $/year, dropping to 1,069,577 $/year after incremental evolution (Figure 4.3). After distortion of the solution space and further incremental evolution, an optimum network with 6 units is obtained with a cost of 1,059,807 $/year (Figure 4.4).

Also other simple methods are successful. The grid following pinch analysis consists of 7 bands (Table 4.2.a) that can be reduced to 4 by merging bands 1 and 2, 4 and 5, 6 and 7. The heating in the first band can be distributed over cold streams C1 and C2 (Table 4.2.b, case A) or concentrated on C2 (Table 4.2.c, Case B).

Using the 4 band grids, initial networks can be synthesised by hand, or by using LP with minimum area as parameter. Band 3 is identical in both cases A and B and 2 different load distributions are possible with the same area but with different cost, as shown in Figure 4.5. Four combinations are developed as initial design and further optimised by incremental evolution. The results are:

- case A with alternative 1, cost 1,059,807 $/year (Figure 4.4) (optimum network)
- case A with alternative 2: cost 1,060,473 $/year (Figure 4.6)
- case B with alternative 1: same network as for case A with alternative 1
- case B with alternative 2: cost 1,062,915 $/year (Figure 4.7)

All final networks have 6 units.

[4.1] K.K. Trivedi, B.K. O'Neill, J.R. Roach, R.M. Wood, Systematic energy relaxation in MER heat exchanger networks, Comput. Chem. Engng. 14 (1990) 606.

[4.2] Jezowski, J., Bochenek, R. and Jezowski, A., Loop breaking in heat exchanger networks by mathematical programming, Applied Thermal Engineering, 21, 1429-1448 (2001).

[4.3] E. Rezaei, S. Shafiei, An NLP Approach for Evolution of Heat Exchanger Networks Designed by Pinch Technology, Iranian Journal of Chemical Engineering, Vol. 5, No. 1 (Winter), 2008, IAChE, 13-21.

Table 4.1

Tsupply °C	Ttarget °C	Heat kW	DT-Shift K	U*f kW/K,m²	Descript -
280	60	6600	10	0.2	H1
180	20	7200	10	0.2	H2
100	200	4000	10	0.2	C1
120	260	8400	10	0.2	C2
300	300	5600		0.2	Heating
5	10	7000		0.2	Cooling

Cost data

Heating : 120 \$/kW,year Cooling : 10 \$/kW,year

Area Cost (\$) = 30000 + 750 x Area $^{0.81}$

Annual Area Cost (\$/year) = 9663 + 241.6 x Area $^{0.81}$

Table 4.2

Table 4.2 a

Descriptic	Band	1	2	3	4	5	6	7	mcp (kW/K)
Heating	300.1	300.0	300.0						
H1			280.0	180.0	132.0	121.3	60.0		30.0
H2				180.0	132.0	121.3	60.0	20.0	45.0
C1		200.0	186.0	156.0	120.0	100.0			40.0
C2	260.0	200.0	186.0	156.0	120.0				60.0
Cooling						10.0	6.4	5.0	

Table 4.2 b

Descriptic	Band	1	2	3	4	mcp (kW/K)
Heating	300.1	300.0				
H1		280.0	180.0	121.3	60.0	30.0
H2			180.0	121.3	20.0	45.0
C1	200.0	186.0	156.0	100.0		40.0
C2	260.0	186.0	156.0	120.0		60.0
Cooling				10.0	5.0	

Table 4.2 c

Descriptic	Band	1	2	3	4	mcp (kW/K)
Heating	300.1	300.0				
H1		280.0	180.0	121.3	60.0	30.0
H2			180.0	121.3	20.0	45.0
C1		200.0	156.0	100.0		40.0
C2	260.0	176.7	156.0	120.0		60.0
Cooling				10.0	5.0	

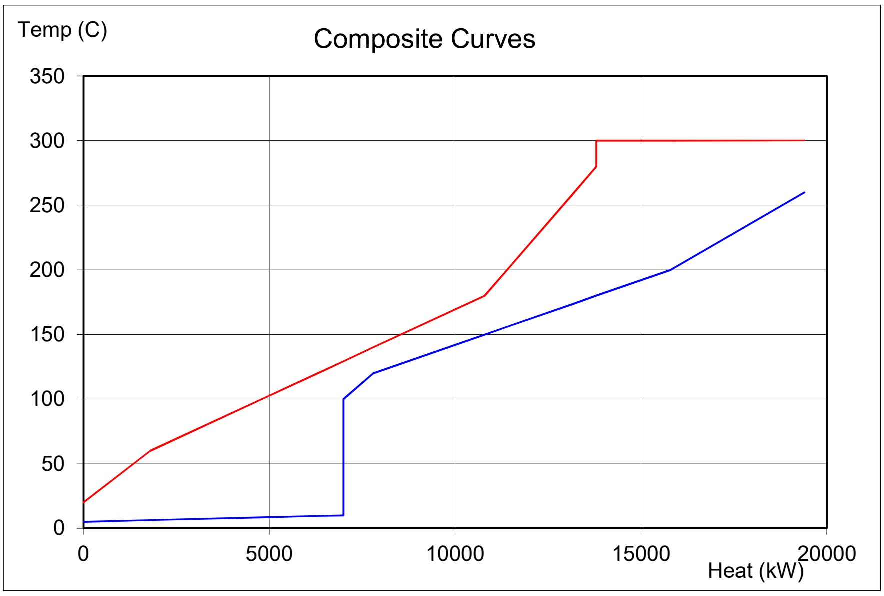


Figure 4.1

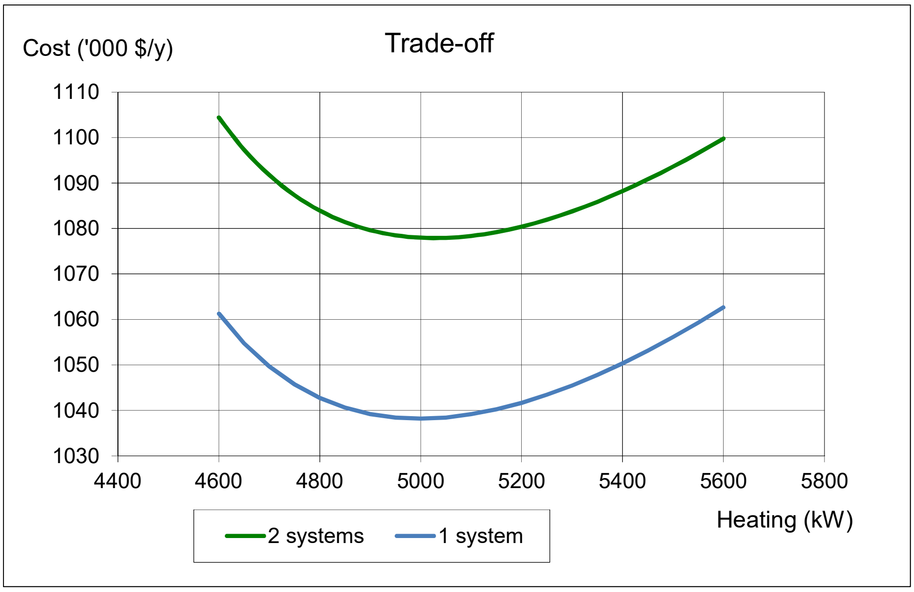


Figure 4.2

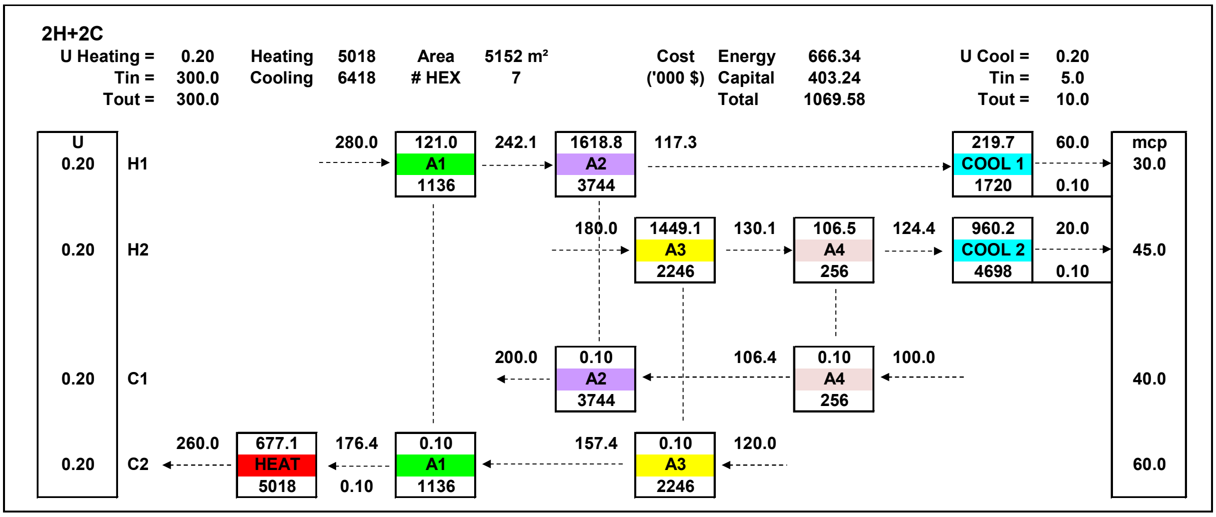


Figure 4.3

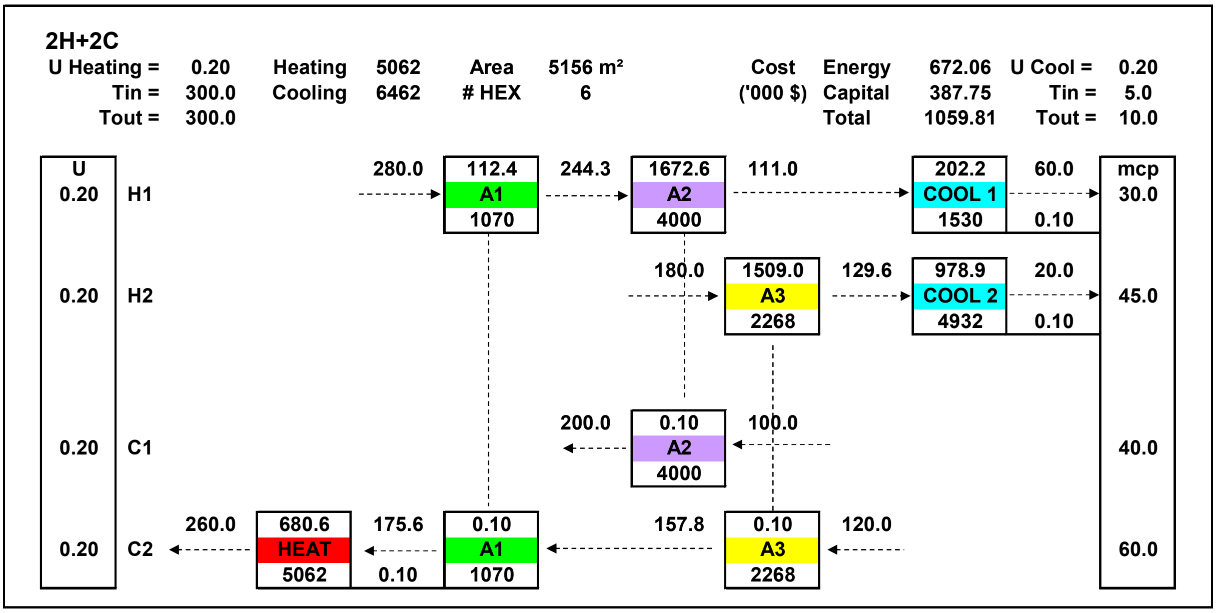


Figure 4.4

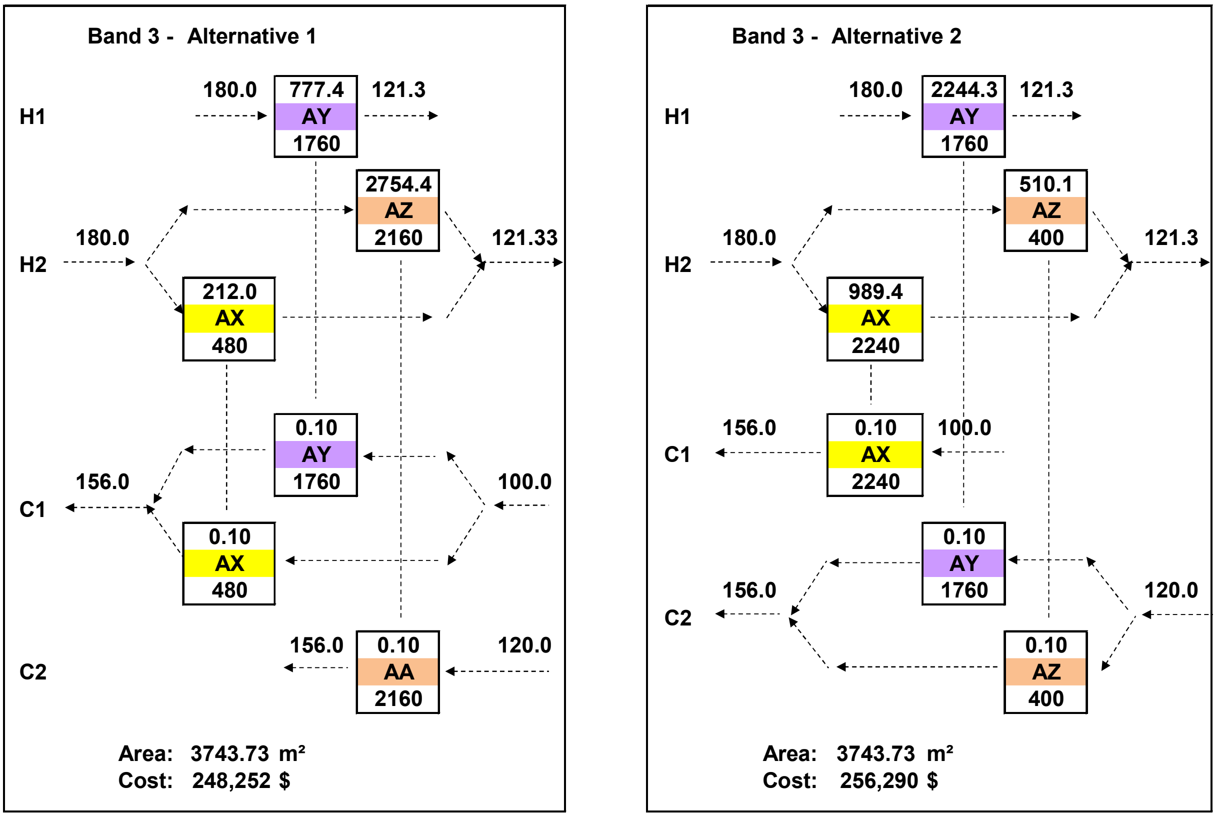
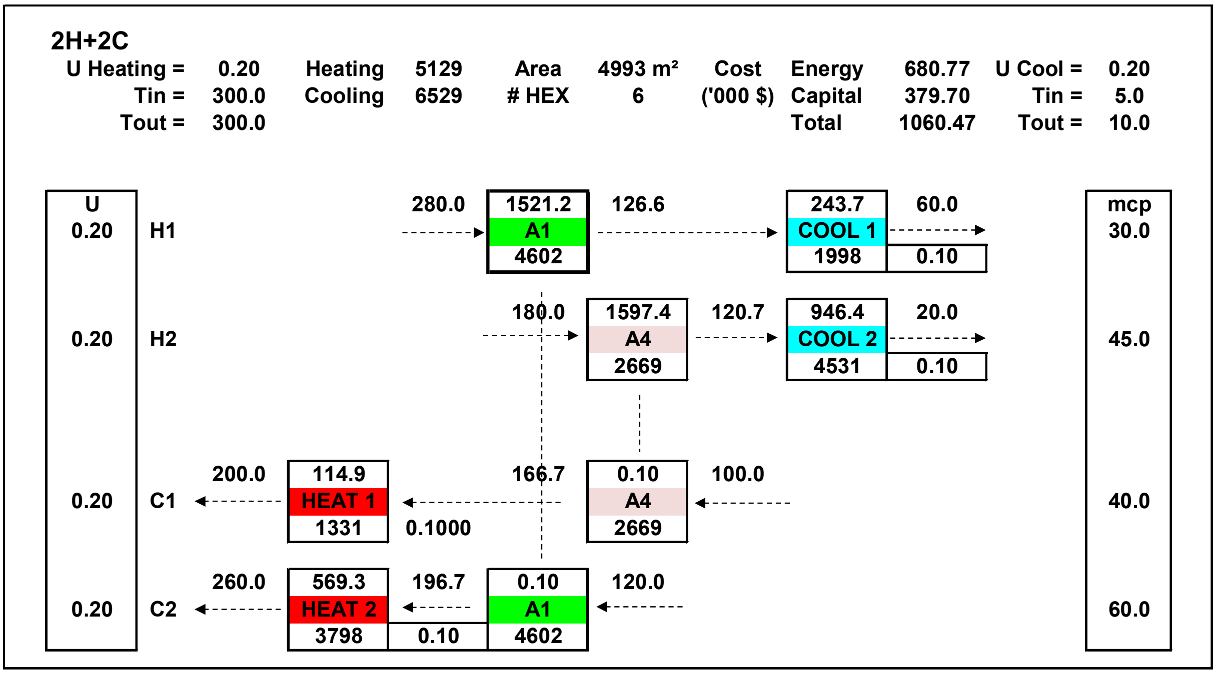


Figure 4.5



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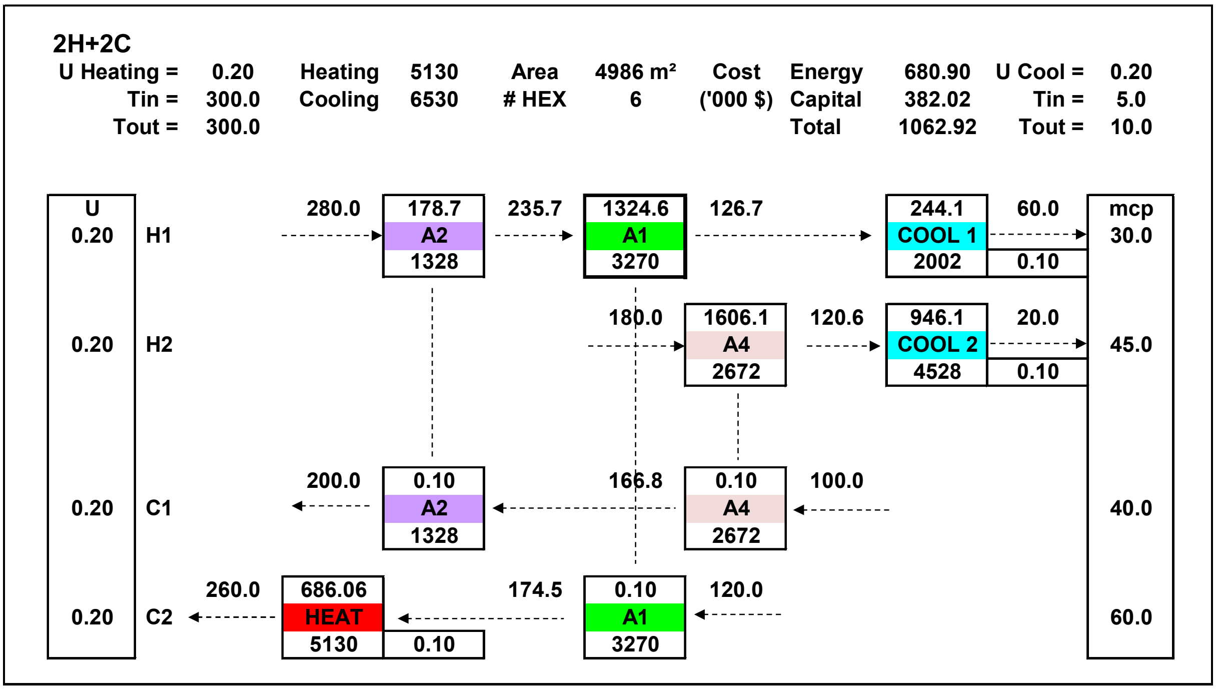


Figure 4.7

5. Example from Linnhoff, Ahmad and Zhu.

Example 5, from Linnhoff and Ahmad [5.1] was also studied by Zhu et al. [5.2] and by Wang et al. [5.3]. The data set is given in Table 5.1. Energy consumption in the table corresponds with an overall DTMin of 10 K. Cost data were taken from Zhu with the annuity factor of 0.2953 as used by Wang.

Composite Curves are shown in Figure 5.1. The curves are parallel between the supply temperatures of cold streams C1 and C2 and C2 will be seen as the stream causing the pinch.

With reference to the trade-off curves of Figure 5.2, a more appropriate optimum heating load would be 7,500 kW with a targeted cost between 1,750 k$ and 1,825 k$ and with 5 to 7 units.

Application of pinch design rules (tick-off) leads to a network with 8 units and a cost of 1,816,702 $/year, dropping to 1,815,291 $/year after incremental evolution (Figure 5.3).

In applying the tick-off procedure above the pinch, as an alternative for the matches H1-C2 and H2-C1, also the matches H1-C1 and H2-C2 satisfy the mcp rule. This combination leads to a network also with 8 units and a cost of 1,842,151 $/year, dropping to 1,833,433 $/year after incremental evolution (Figure 5.4). After distortion of the solution space and further incremental evolution, a network with 7 units is obtained with a cost of 1,809,483 $/year (Figure 5.5).

[5.1] Linnhoff, B., and S. Ahmad. 1990. "Cost Optimum Heat Exchanger Networks—1. Minimum Energy and Capital Using Simple Models for Capital Cost*." Computers & Chemical Engineering* 14 (7): 729–750. doi:http://dx.doi.org/10.1016/0098-1354(90)87083-2.

[5.2] Zhu, Xin X. 1997. "Automated Design Method for Heat Exchanger Network Using Block Decomposition and Heuristic Rules." *Computers & Chemical Engineering* 21 (10): 1095–1104.

[5.3] Jinyang Wang, Guomin Cui, Yuan Xiao, Xing Luo & Stephan Kabelac (2016):
Bi-level heat exchanger network synthesis with evolution method for structure optimization and memetic particle swarm optimization for parameter optimization, Engineering Optimization,
DOI: 10.1080/0305215X.2016.1191803

Table 5.1

Tsupply K	Ttarget K	Heat kW	Shift K	U*f kW/m²,K	Description -
423	323	20000	5	0.2	H1
443	313	13000	5	0.2	H2
323	393	21000	5	0.2	C1
353	383	15000	5	0.2	C2
453.01	453	7000		0.2	Heating
293	313	4000		0.2	Cooling

Cost data
Heating: 110 $/kW,year Cooling: 10/kW,year
Area Cost ($): 30800 + 750 x Area $^{0.81}$

Life time: 6 years Interest rate: 10% annuity factor used: 0.2953
Annual Area Cost ($/year): 9094.01 + 221.45 x Area $^{0.81}$

Figure 5.1

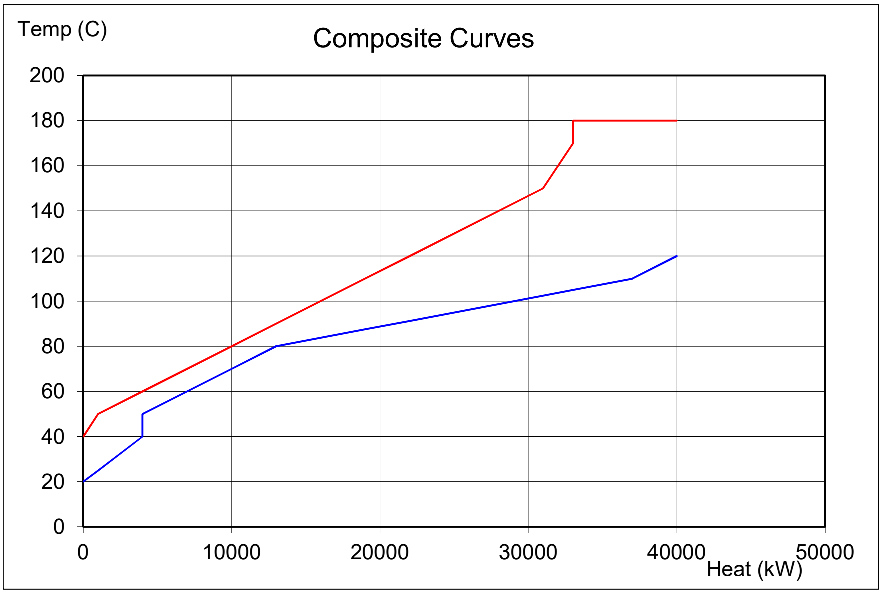
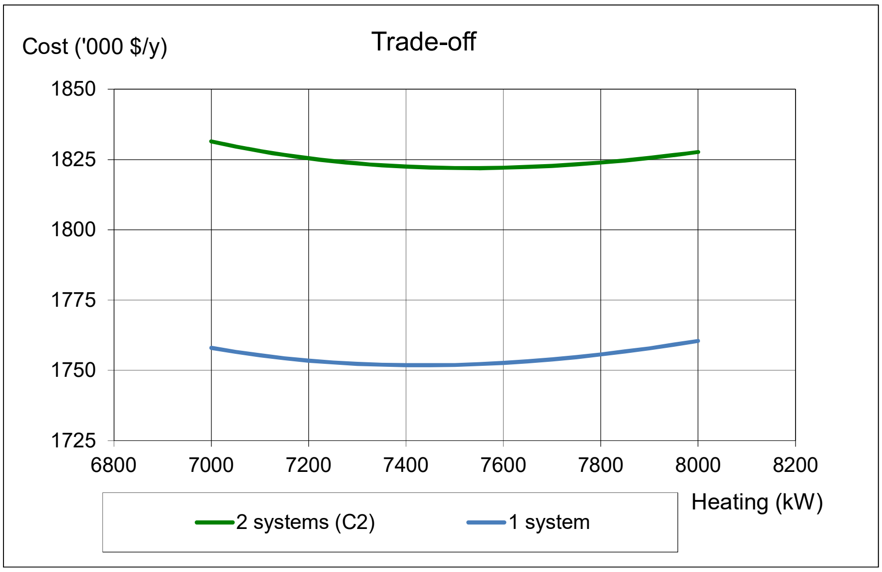


Figure 5.2



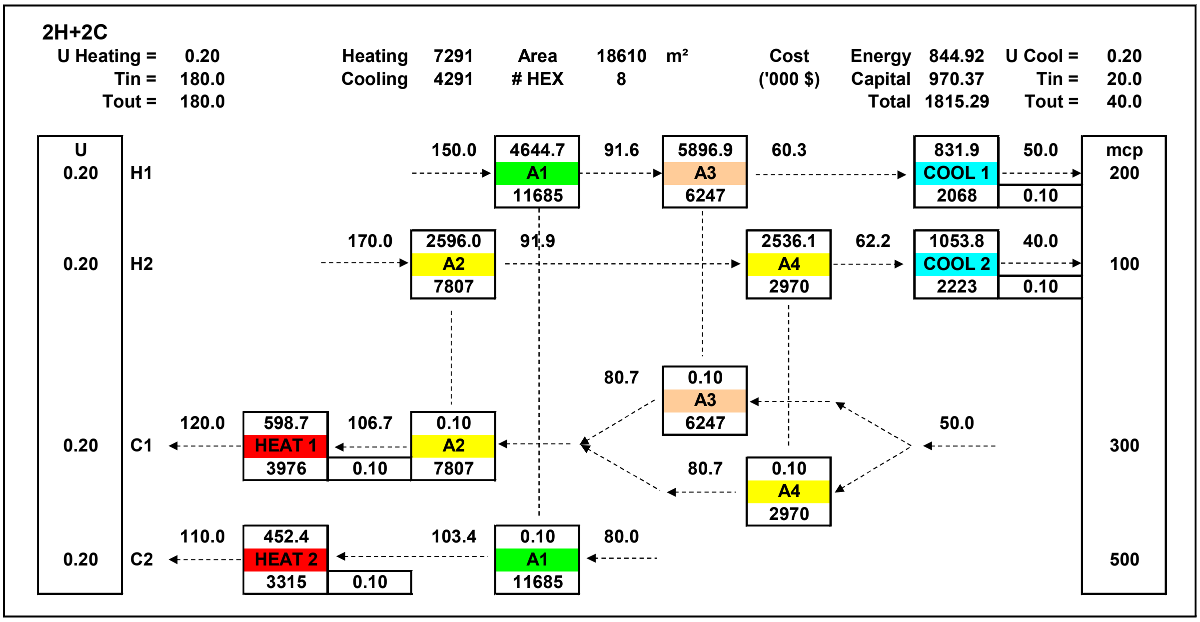


Figure 5.3

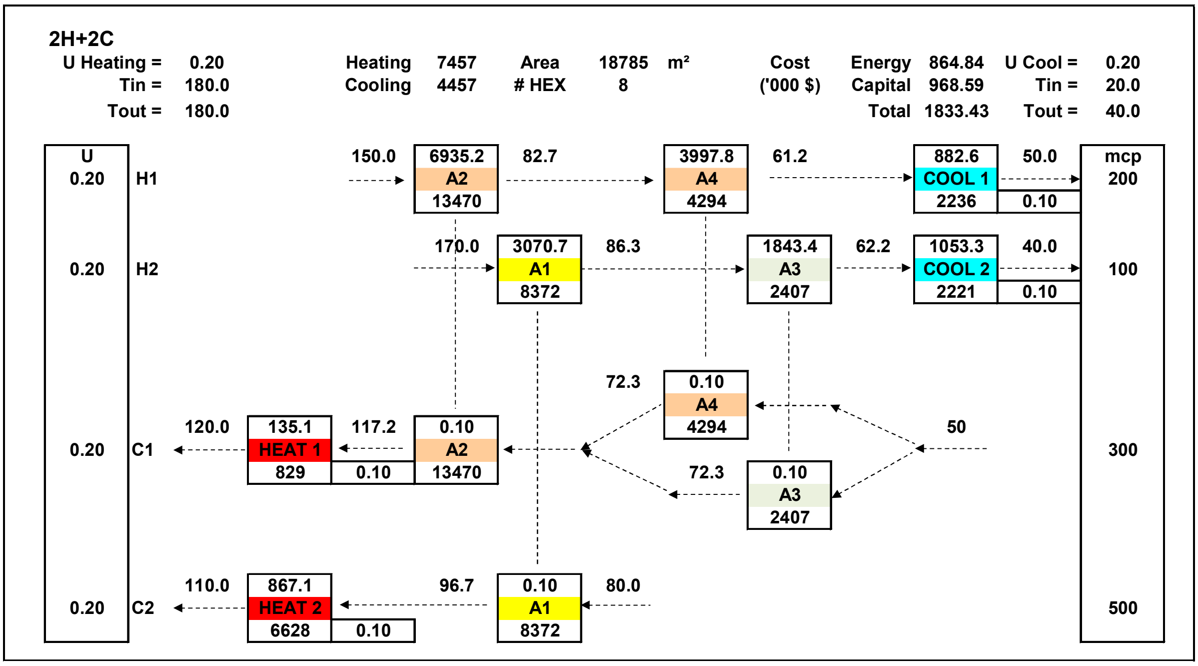


Figure 5.4

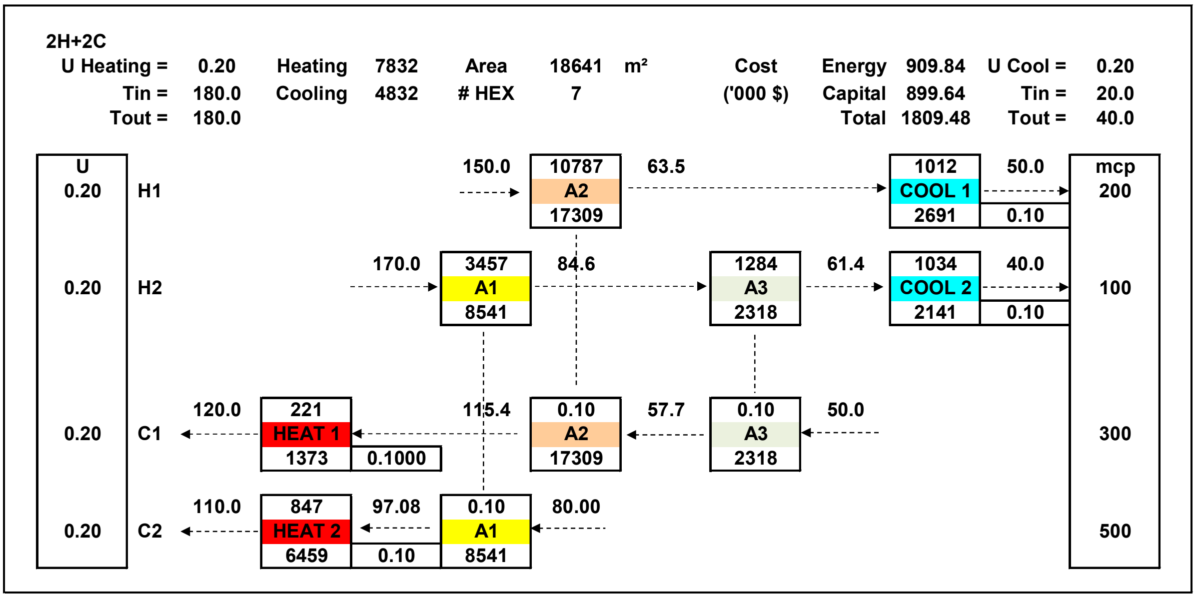


Figure 5.5

6. Example from Yee and Grossmann

Example 6 is based on stream data from Linnhoff et al [6.1], adapted to the present form by Yee and Grossmann [6.2]. It was also studied by Zhu [6.3], Gcaba [6.4], Ren [5], and Rezaei [3.6] with the same cost data. The data set is given in Table 6.1. Energy consumption in the table corresponds with an overall DTMin of 10 K.

Composite curves, in which a threshold problem has been anticipated are shown in Figure 6.1. The trade-off curves in Figure 6.2 suggest that a cost optimum can be obtained without heating. Said curves have been simplified in assuming the same exchanger area cost for heaters as for other exchangers; this has no impact on the conclusion.

The threshold problem can still be considered as pinched and treated as such. Application of the tick-off procedure leads to a network with 6 units and a cost of 81,107 $/year, reduced to 79,233 $/year after optimisation by incremental evolution (Figure 6.3). By distortion of the solution space, the number of units can be reduced to 5; the cost of the network will increase to 80,910 $/year (Figure 6.4).

The grid from the analysis shows 6 integration bands; application of LP on that grid generates a network with 12 units which, after incremental evolution, develops automatically into the optimum network with 6 units and a cost of 78,704 $/year (Figure 6.5).

The case was also studied by Zamora & Grossmann [6.7] with different area cost data as mentioned in Table 6.1; these area cost data were also used by Lee & Grossmann [6.8], Pariyani et al [6.9], Petterssen [6.10] and Gorji-Bandpy et al [6.11].

Application of the tick-off procedure leads to a network with 6 units and a cost of 85,210 $/year, reduced to 84,535 $/year after optimisation by incremental evolution (Figure 6.6). The network has the same structure as with the cost data of Yee & Grossmann (Figure 6.3), with differences in the heat loads only. By distortion of the solution space, also here the number of units can also be reduced to 5 with a cost increase of the network to 85,970 $/year.

The 6 integration bands from the analysis can be reduced to 4 as shown in Table 6.2. Application of LP on that grid results into a network of 7 units which, after incremental evolution, results into a network with 6 units, 1 split and a cost of 83,937 $/year (Figure 6.7).

The 4 integration bands can further be reduced to 3 as shown in Table 6.3. Application of LP on that grid results into a network of 6 units which, after incremental evolution, results into a network with 5 units, 2 splits and a cost of 82,428 $/year (Figure 6.8). Relocation of heat exchanger A4 on hot stream H1 leads to a further marginal cost reduction to 82,363 $/year as shown in Figure 6.9.

A summary of the results is shown in Table 6.4.

[6.1] Linnhoff, B., Townsend, D. W., Boland, D., & Hewitt, G. F. (1982). A user guide on process integration for the efficient use of energy - The Institution of Chemical Engineers.

[6.2] T. F. Yee, Grossmann and Z. Kravanja, Simultaneous Optimization Models for Heat Integration – I. Area and Energy Targeting and Modelling of Multi-stream Exchangers, Computers Chem. Engng, Vol. 14, No. 10, 1990, pp.1151-1164.

[6.3] Xin X. Zhu, Strategies for Optimization in Heat Exchanger Network Design, PhD Thesis University of Adelaide, Australia (January 1994).

[6.4] Sibusiso J. Gcaba, Design of Consistently Near-optimal Heat Exchanger Networks by a Two-stage Optimisation Approach, MSc thesis University of Cape Town, South Africa (May 1998).

[6.5] Yikai Ren, A Recursive Design Method for Heat Exchanger Networks, PhD Thesis University of Adelaide, Australia (March 2000).

[6.6] E. Rezaei E., Shafiei S., An Efficient Coupled Genetic Algorithm-NLP Method for Heat Exchanger Network Synthesis, Iranian Journal of Chemical Engineering Vol. 5, No. 1 (Winter), 2008, IAChE.

[6.7] Juan M. Zamora and Ignacio E. Grossmann, A global MINLP optimization algorithm for the synthesis of heat exchanger networks with no stream splits, *Computers chem. Engng* Vol. 22, No. 3, pp. 367-384, 1998

[6.8] Sangbum Lee and Ignacio E. Grossmann, A Global Optimization Algorithm for Nonconvex Generalized Disjunctive Programming and Applications to Process Systems, Department of Chemical Engineering, Carnegie Mellon University, Pittsburgh, PA 15213.

[6.9] Ankur Pariyani, Abhigyan Gupta, Pallab Ghosh, Design of heat exchanger networks using randomized algorithm, Computers and Chemical Engineering 30 (2006) 1046–1053.

[6.10] F. Pettersson, Heat exchanger network design using geometric mean temperature difference, Computers and Chemical Engineering 32 (2008) 1726–1734.

[6.11] Mofid Gorji-Bandpy, Hossein Yahyazadeh-Jelodar, Mohammadtaghi Khalili, Optimization of heat exchanger network, Applied Thermal Engineering 31 (2011) 779-784.

Table 6.1

Tsupply K	Ttarget K	Heat kW	DT-Shift K	U*f kW/K,m²	Descript -
443	333	3300	5	1.6	H1
423	303	1800	5	1.6	H2
293	408	2300	5	1.6	C1
353	413	2400	5	1.6	C2
450	450	200		4.8	Heating
293	313	600		1.6	Cooling

Cost data Yee & Grossmann [6.2]
Heating : 80 \$/kW,year Cooling : 20 \$/kW,year
Area Cost Exchangers & Coolers (\$/year) = 1000 x Area $^{0.6}$
Area Cost Heaters (\$/year) = 1200 x Area $^{0.6}$

Cost data Zamora & Grossmann [6.7]
Area Cost Exchangers & Coolers (\$/year) = 6250 + 83.26 x Area
Area Cost Heaters (\$/year) = 6250 + 99.91 x Area

Table 6.2

Descript.	mcp (kW/K)	Band		1		2		3		4	
H1	30.00		443.0		436.3		358.6		333.0		
H2	15.00				423.0		358.6		329.7		303.0
C1	20.00				408.0		353.0		293.0		
C2	40.00		413.0		408.0		353.0				
Cooling	20.00								313.0		293.0

Table 6.3

Descript.	mcp (kW/K)	Band		1		2		3	
H1	30.00		443.0		358.6		333.0		
H2	15.00		423.0		358.6		329.7		303.0
C1	20.00		408.0		353.0		293.0		
C2	40.00		413.0		353.0				
Cooling	20.00						313.0		293.0

Table 6.4

Cost data Yee & Grossmann	Cost ($/year)	# units	# splits
Yee & Grossmann (1990)	80275	5	2
	80911	5	0
Zhu (1995) °1)	80274	5	2
Gcaba (1998)	79774	6	0
Ren (2000)	80914	7	1
Rezaei (2008)	79991	6	1
This research	78704	6	1
	79233	6	0
°1) same network as Yee & Grossmann			

Cost data Zamora & Grossmann	Cost ($/year)	# units	# splits
Zamora & Grossmann (1998)	85970	5	0
Lee & Grossmann (1998)	87176	5	0
Pariyani (2006)	85307	6	1
	85972	5	0
Pettersson (2008)	84066	6	1
Gorji-Bandpy (2011)	94603	7	2
This research	82363	5	2
	83937	6	1
	84535	6	0

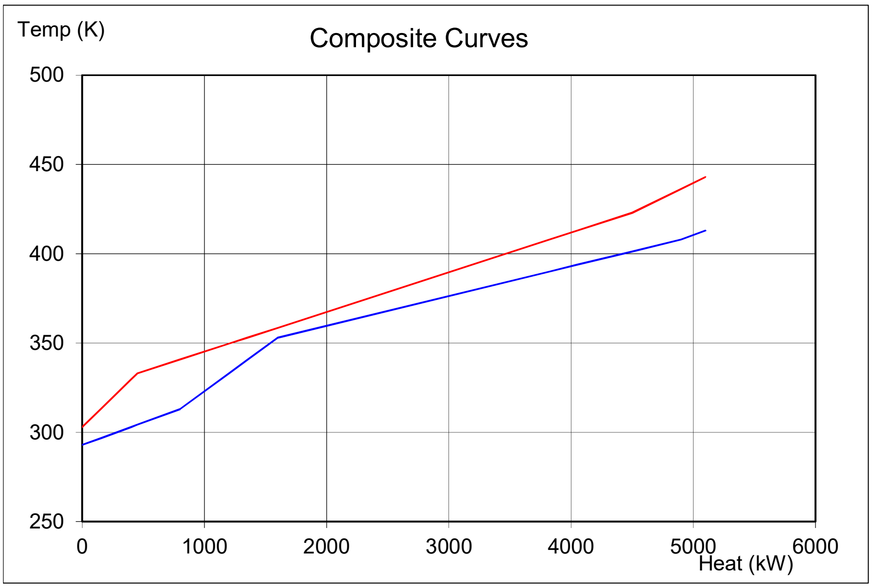


Figure 6.1

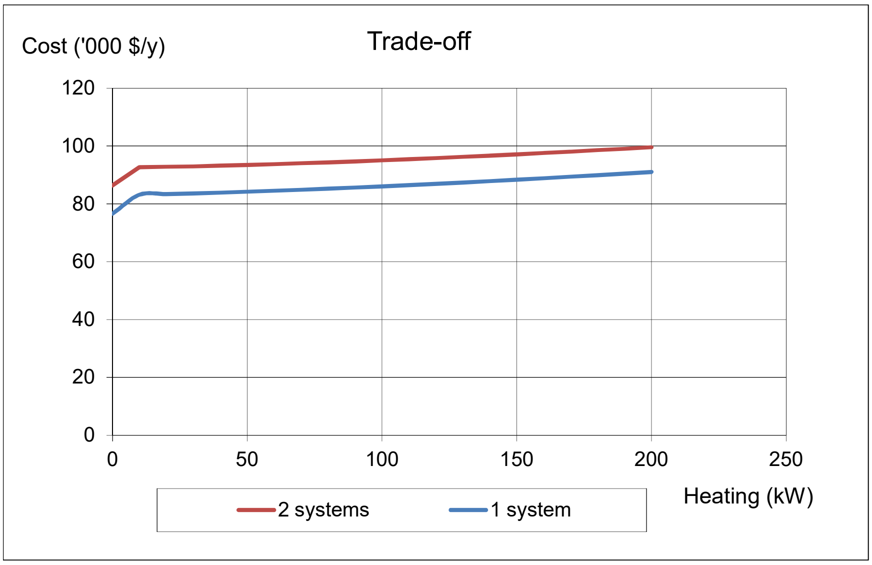
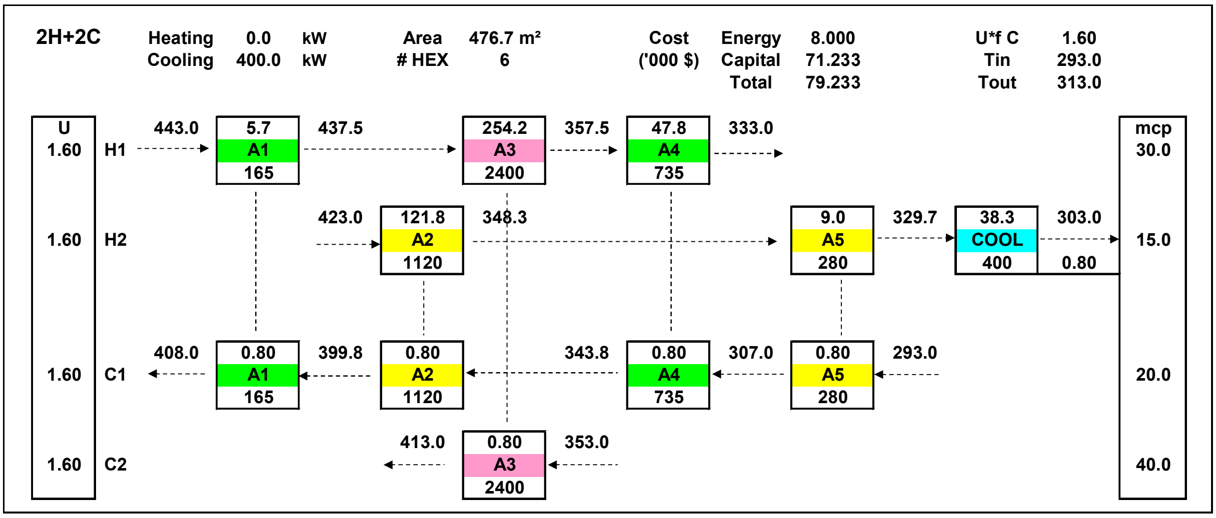


Figure 6.2



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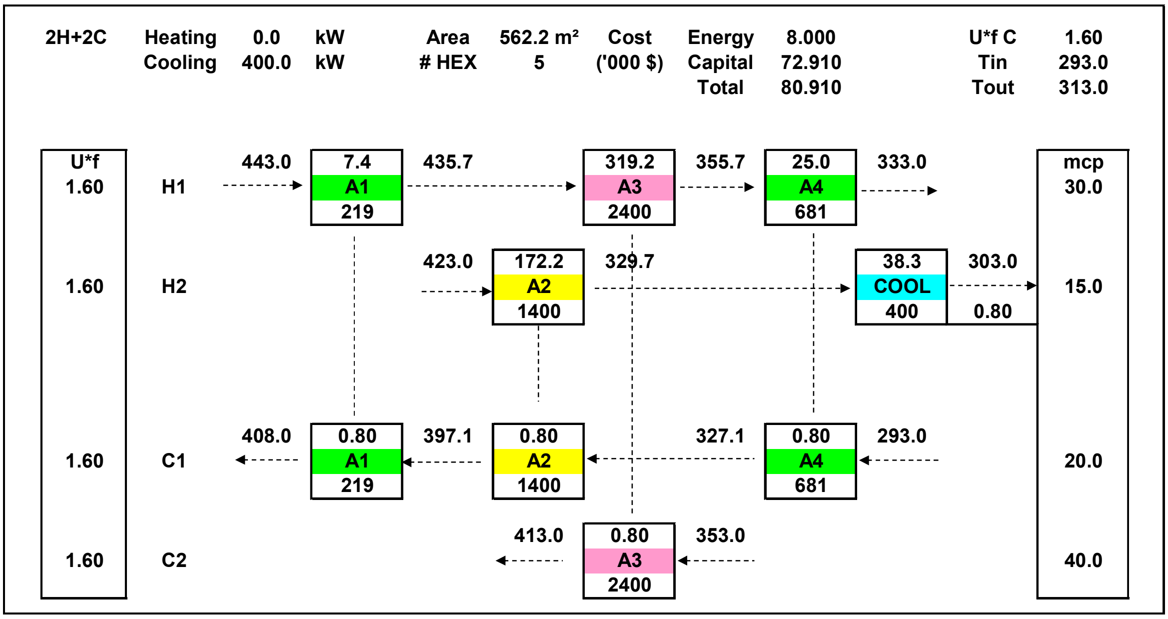
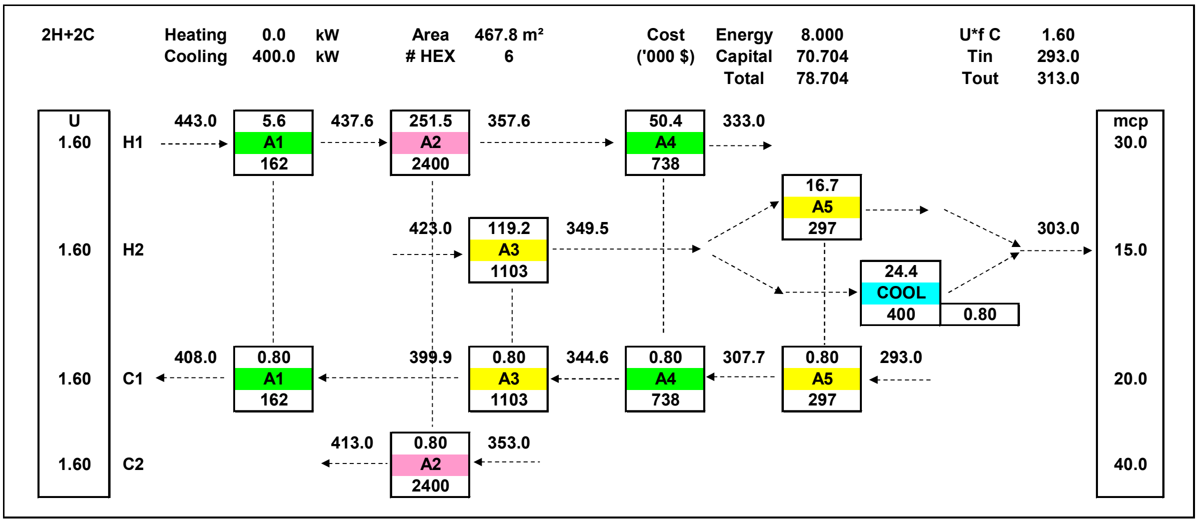


Figure 6.4



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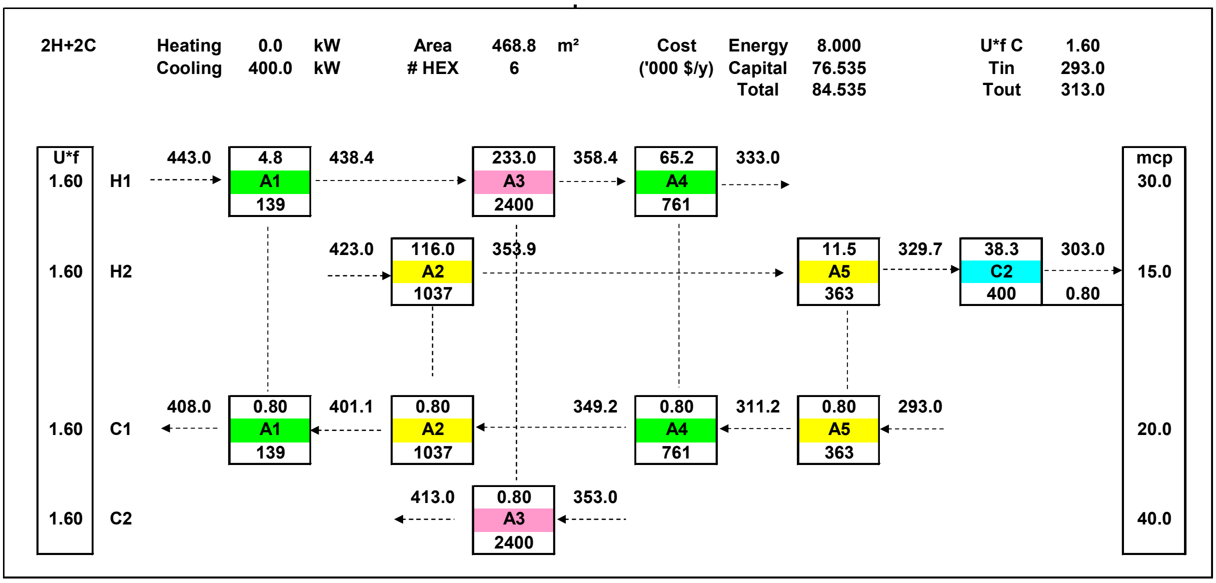


Figure 6.6

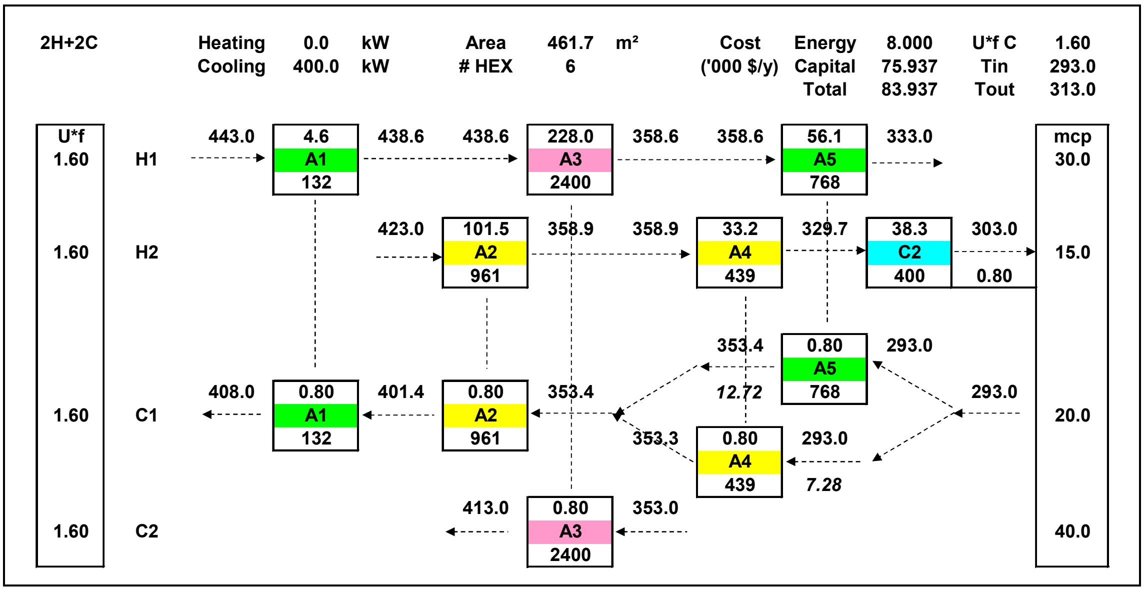
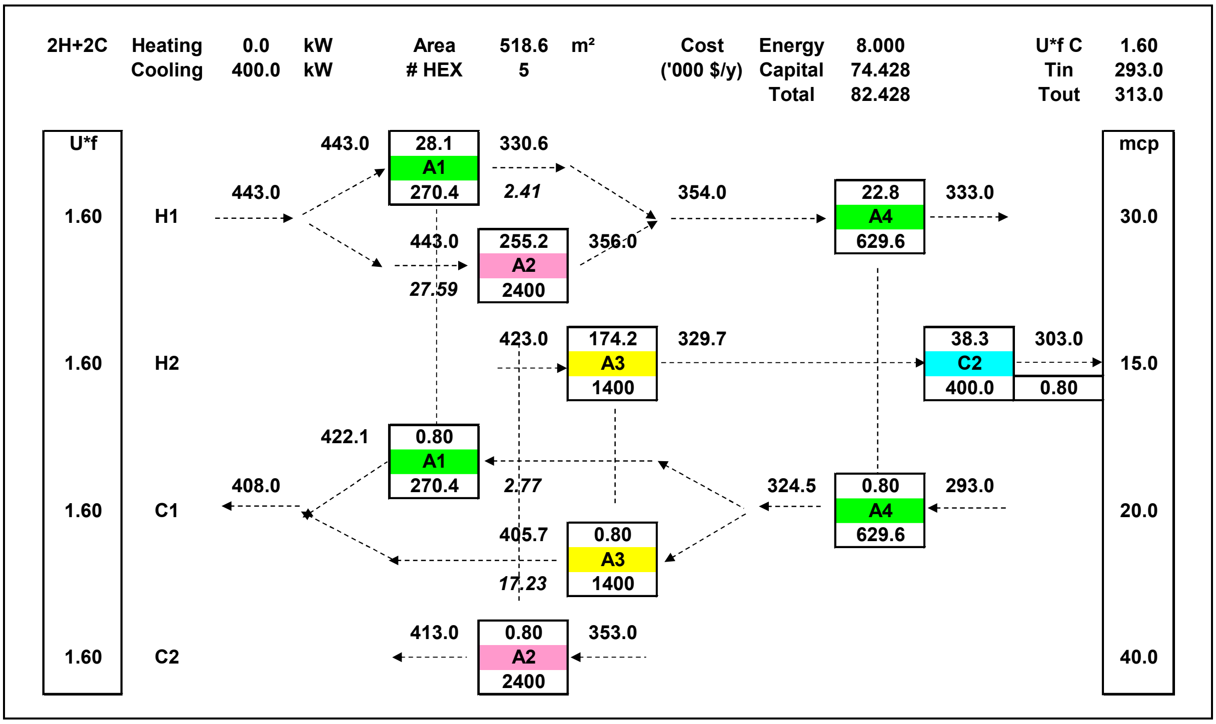


Figure 6.7



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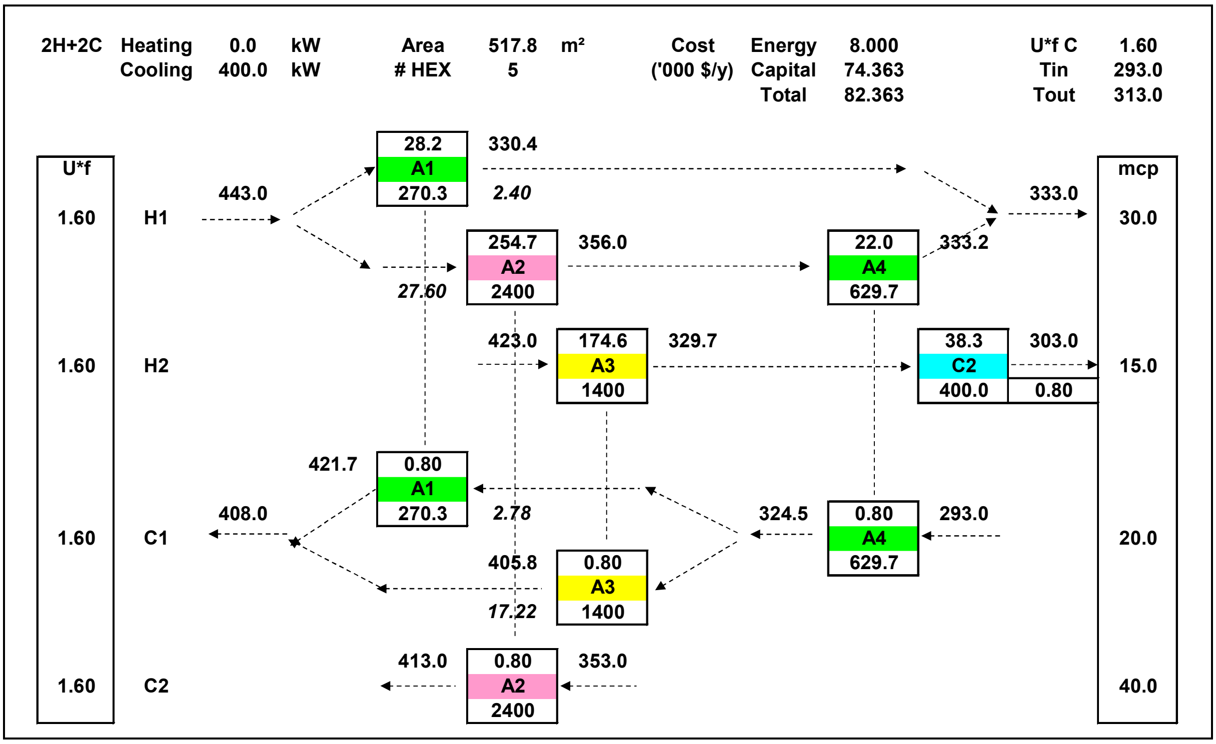


Figure 6.9

7. Example from Gundersen

Example 7 is from Gundersen [7.1]. The data set is given in Table 7.1. Energy consumption in the table corresponds with an overall DTMin of 10 K.

Composite Curves are shown in Figure 7.1. Trade-off curves in Figure 7.2 suggest that a heating load of 640 kW might be appropriate for a cost optimum of around 346,000 $/year for a network with 5 units.

The results are summarised in Table 7.2.

Application of pinch design rules (tick-off) leads to a network with 7 units, reduced to 6 after optimisation by incremental evolution with a cost of 352,719 $/year (Case b, Figure 7.3).

The mcp values at the pinch in combination with the heat loads are such that also a smart tick-off procedure can be used: after matches above the pinch have been chosen, matches below the pinch can be aligned on those above the pinch (Case c) or, alternatively, after matches below the pinch have been chosen, matches above the pinch can be aligned on those below the pinch (Case d). Evolution of Case c leads to the same result as the standard tick-off procedure of Case b. Evolution of Case d leads to the a network with 5 units for a cost of 349,389 $/year (Figure 7.4).

The grid from the analysis has 7 bands; application of LP leads in band 4 to a split of C2 and either H1 (Case e) or H2 (Case f). Evolution of Case e offers limited possibilities and, starting with 7 bands, leads to the same network as Case b. Evolution of Case f without merging bands leads to Case f1 (Figure 7.5) and after merging bands to Case f2 (Figure 7.6). Both results can be further developed by distortion of the solution space into the optimum network of Case f3 (Figure 7.7) with 5 units and a cost of 349,121 $/year.

Finally, swaps can be applied from HEX to Utilities (Case g) leading to the network of Figure 7.8 or vice-versa (Case h), leading to the network of Figure 7.9. All 7 networks are within 1% of the optimum.

[7.1] Gundersen, A Process Integration PRIMER, SINTEF Energy Research, International Energy Agency, 2000.

Table 7.1

Tsupply °C	Ttarget °C	Heat kW	Shift K	U kW/m²,K	Description -
270	160	1980	5	0.5	H1
220	60	3520	5	0.5	H2
50	210	3200	5	0.5	C1
160	210	2500	5	0.5	C2
250	250	600		2.5	Heating
15.0	20.00	400		1.0	Cooling

Cost data

Heating : 200 $/kW,year
Cooling : 20 $/kW,year

Annual Area Cost ($/year) = 4000 + 500 x Area $^{0.83}$

Table 7.2

	Procedure	Initial network				
		Heating kW	Area m²	Cost $/year	# Units -	Ref.
a	Target	640	917.6	365,063	7	
		640	917.6	345,946	5	
b	Pinch - tick-off	640	1166.9	386,960	7	
	after evolution	637	963.2	352,719	6	Fig.7.3
c	Smart tick-off 1 (1)	640	998.0	358,595	6	
	after evolution	637	963.2	352,719	6	ref. b
d	Smart tick-off 2 (2)	640	1320.3	383,498	6	
	after evolution	592	1167.4	349,389	5	Fig.7.4
e	LP on Grid - split on H1	640	917.6	398,961	14	
	after evolution	637	963.2	352,719	6	ref. b
f	LP on Grid - split on H2	640	917.6	400,015	14	
f1	start with 7 bands	664	1009.4	349,744	6	Fig.7.5
f2	start with 5,4 or 3 bands	660	1015.8	350,055	6	Fig.7.6
f3	further evolution of f1 or f2	593	1158.8	349,121	5	Fig.7.7
g	Swap from HEX to Utility				from Fig.7.5, Fig.7.6	
		663	1016.5	349,952	6	Fig.7.8
h	Swap from Utility to HEX				from Fig.7.8	
		661	1019.8	350,268	6	Fig.7.9

(1) Smart tick-off 1: start with matches above pinch and align matches below pinch on those above pinch

(2) Smart tick-off 2: start with matches below pinch and align matches above pinch on those below pinch

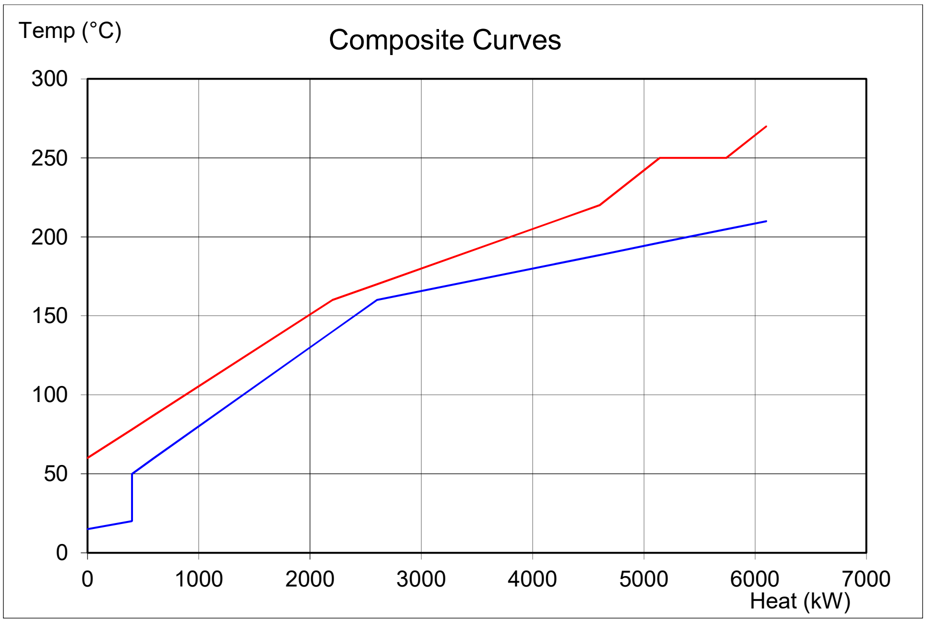


Figure 7.1

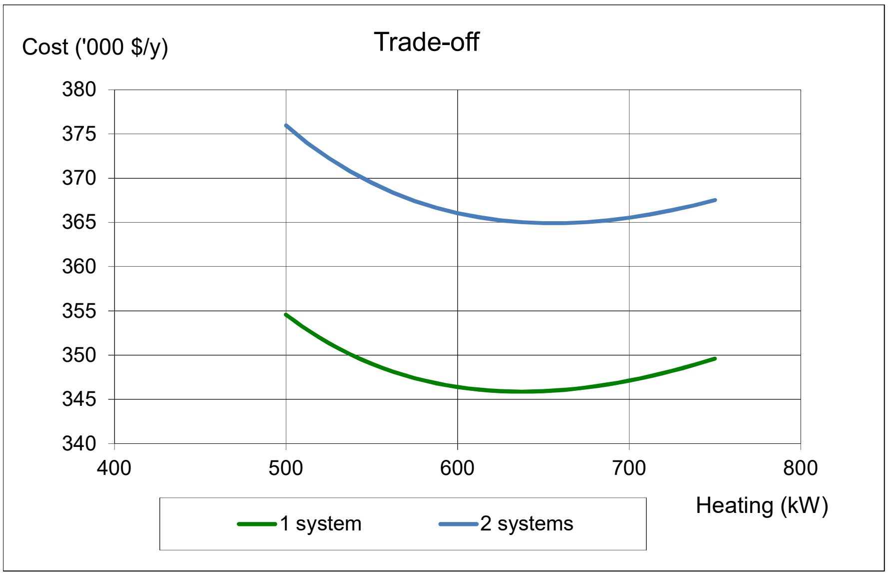
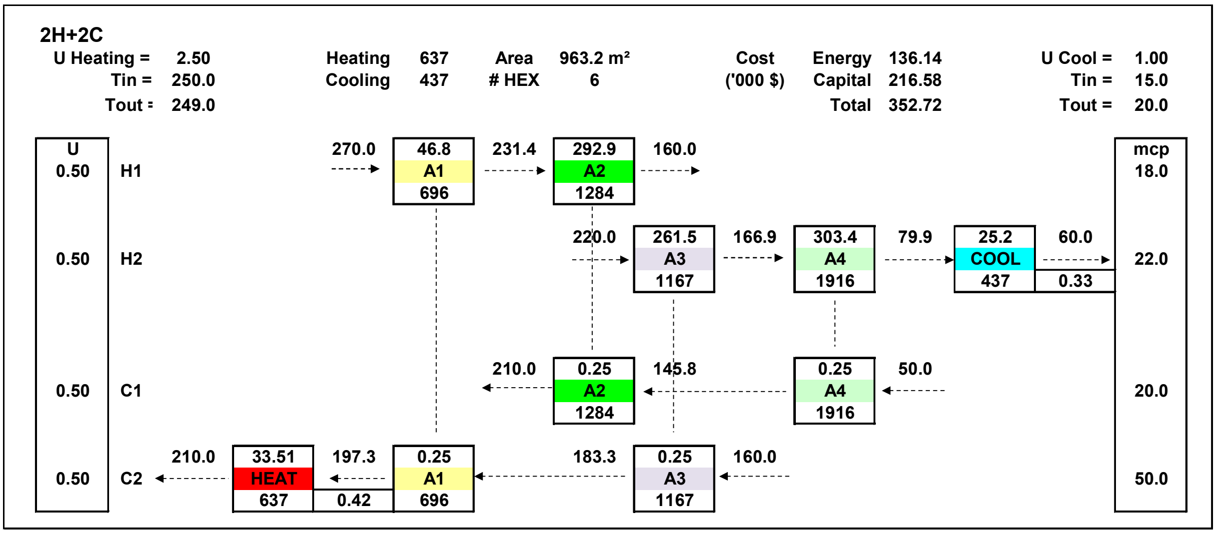


Figure 7.2



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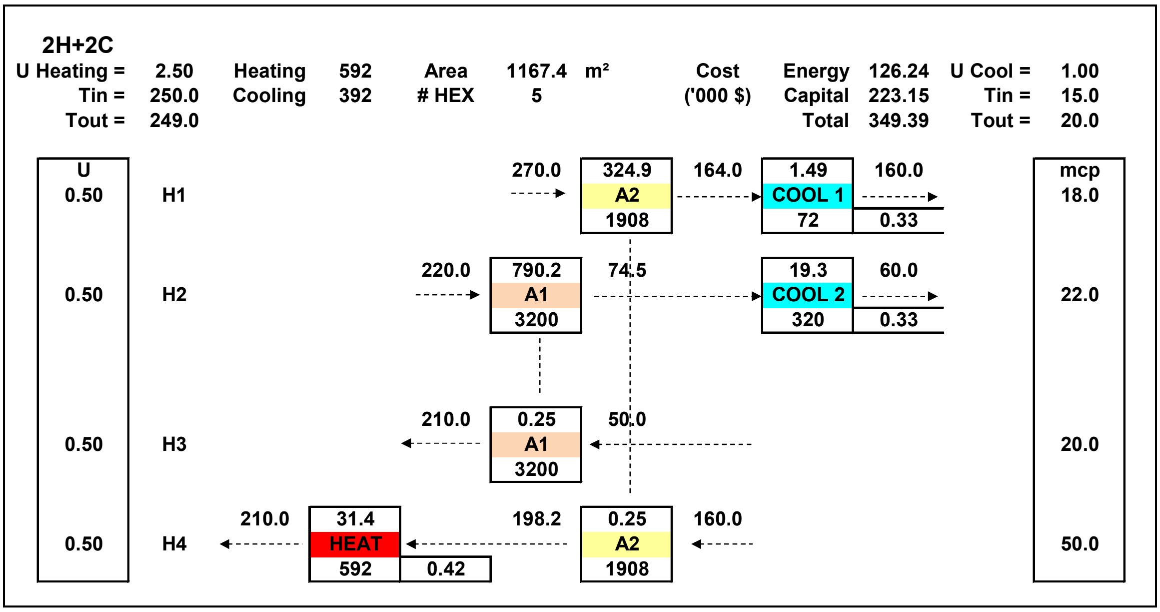


Figure 7.4

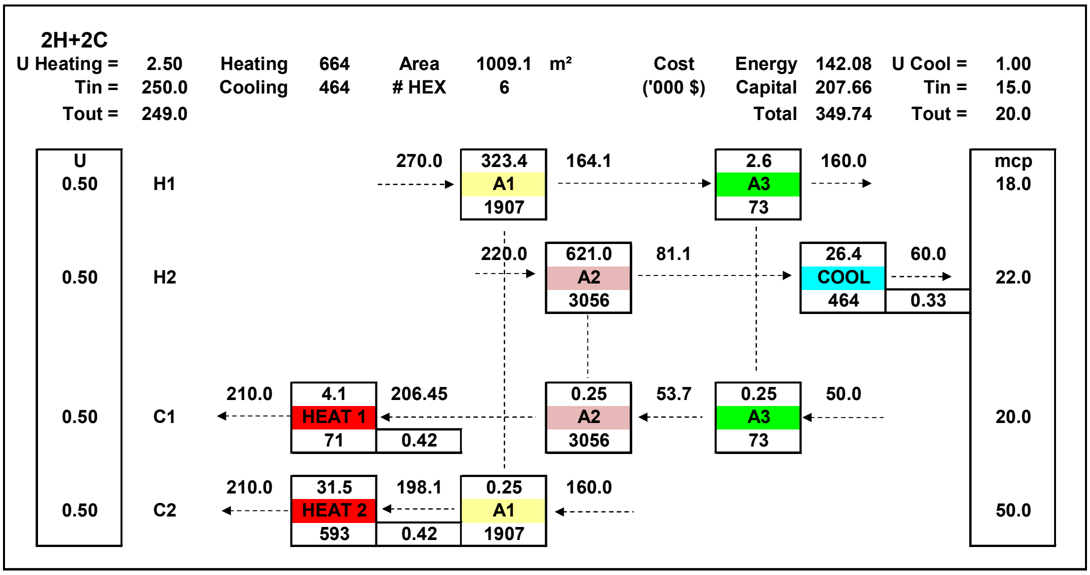


Figure 7.5

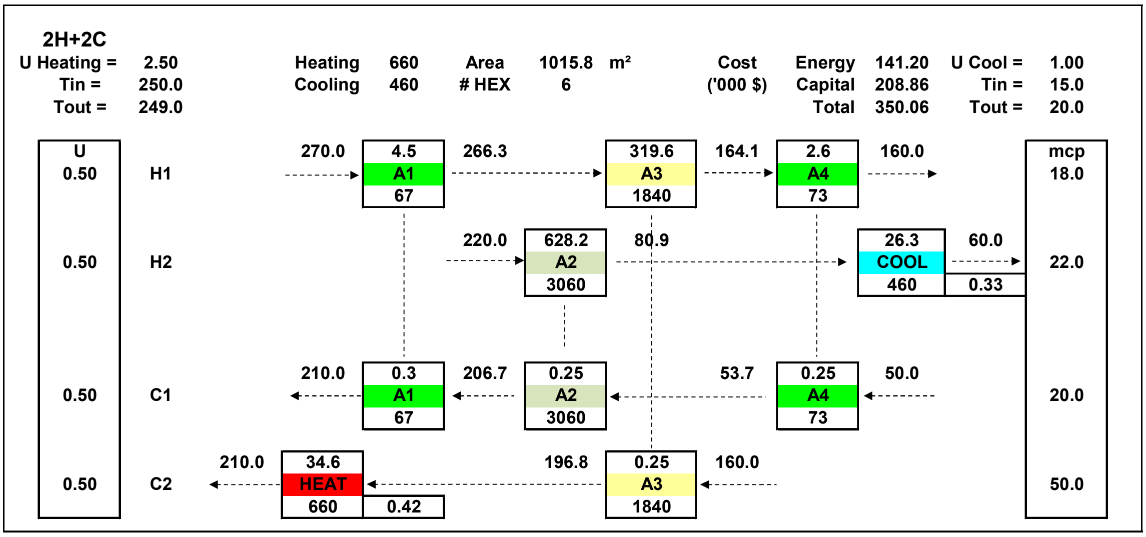


Figure 7.6

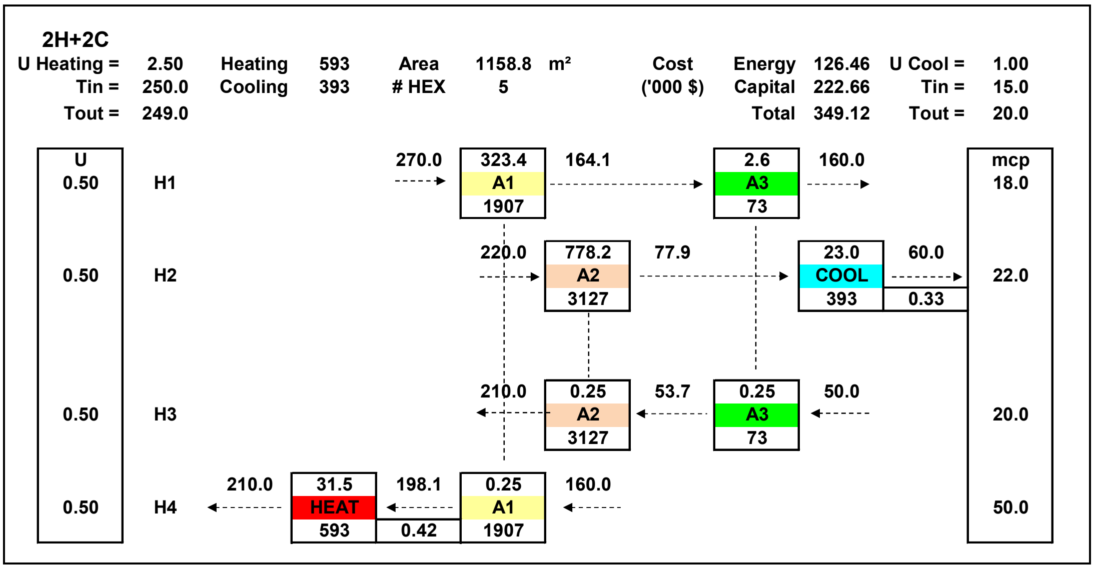


Figure 7.7

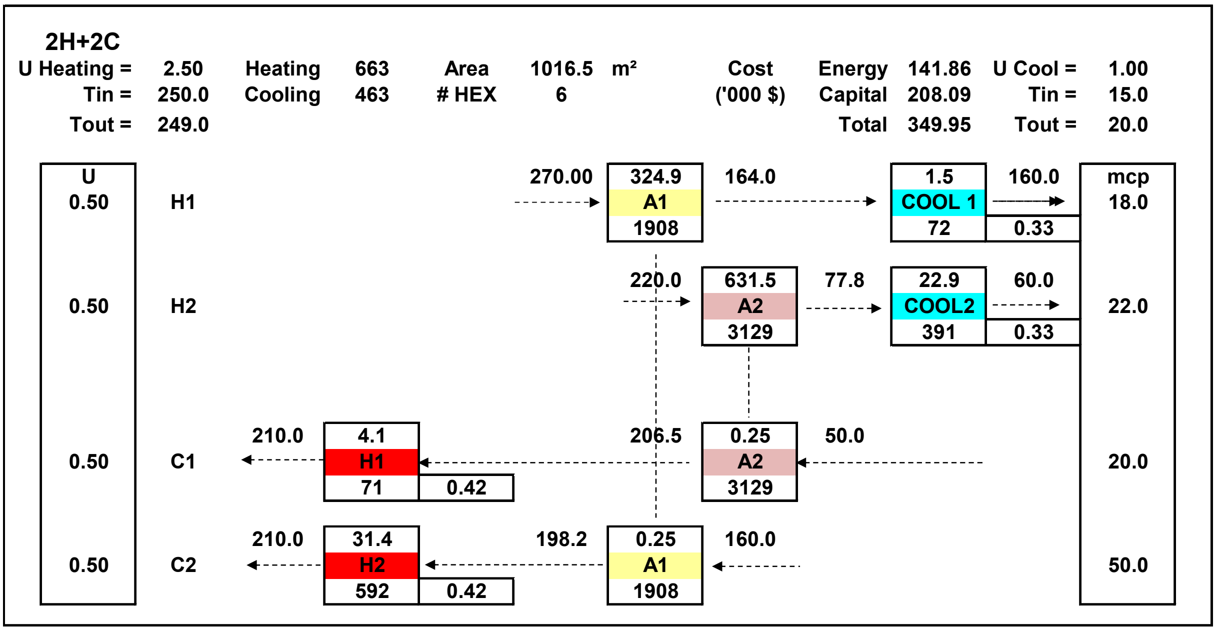


Figure 7.8

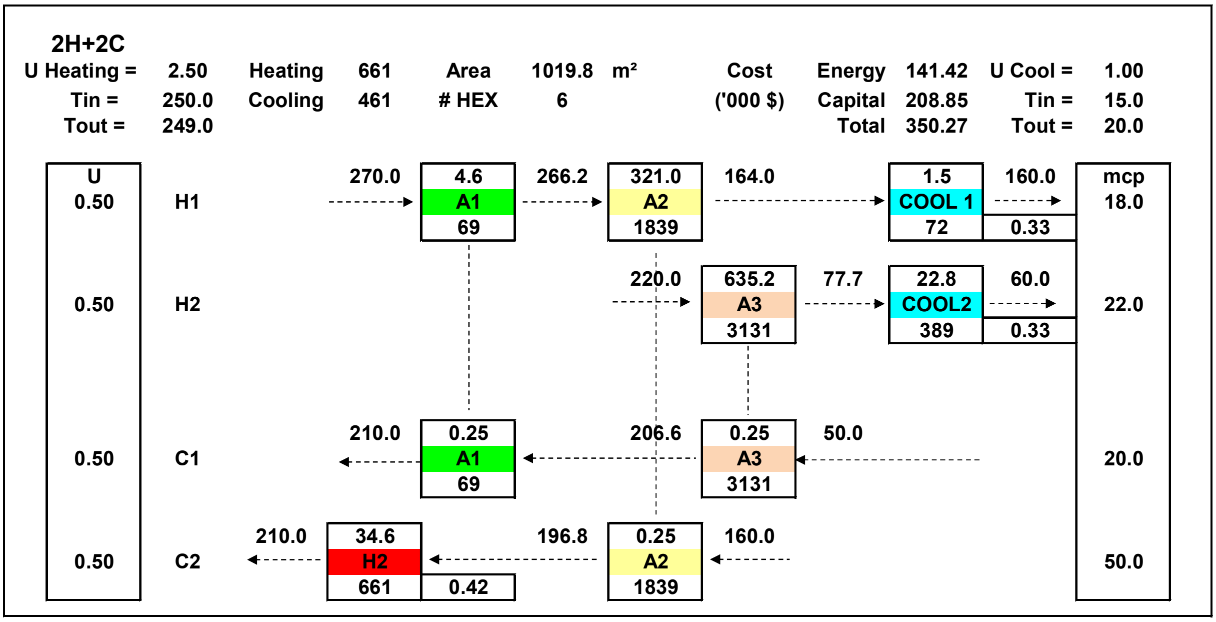


Figure 7.9

8. Example from Colberg and Morari

Example 8, originally from Colberg and Morari [8.1], was also treated by Yee et al.[8.2]. The data set is given in Table 8.1. Energy consumption in the table corresponds with an overall DTMin of 10 K.

Composite curves are shown in Figure 8.1; Trade–off classic and with crisscross are shown in Figure 8.2. Trade-off with crisscross optimised for shift values as shown in Table 8.2 for an optimum heating of 733 kW is shown in Figure 8.3; the area target is 175 m², the cost target 100,467 $/year.

The data set was studied for a heat load of 620 kW mentioned in [8.1] and [8.2] and for heat loads resulting from the trade-off analysis (740 kW for the classic and 733 kW for the crisscross analysis). The results are summarised in Table 8.3.

The tick-off procedure followed by incremental evolution generates the same network for the different initial heat loads. The best network (cost 98,950 $/year) is generated in the most systematic way by starting from a grid, optimized with crisscross, application of LP and incremental evolution.

[8.1] R. D. Colberg and M. Morari, Area and Capital Cost Targets for Heat Exchanger Network Synthesis with Constrained Matches and Unequal Heat Transfer Coefficients, Computers Chem. Engng, Vol. 14, No. 1, 1990, pp. l-22,

[8.2] T. F. Yee, Gossmann and Z. Kravanja, Simultaneous Optimization Models for Heat Integration – I. Area and Energy Targeting and Modeling of Multi-stream Exchangers, Computers Chem. Engng, Vol. 14, No. 10, 1990, pp.1151-1164.

Table 8.1

Tsupply K	Ttarget K	Heat kW	DT-Shift K	U*f kW/K,m²	Descript -
395	343	208	5	2.0	H1
405	288	702	5	0.2	H2
293	493	1000	5	2.0	C1
353	383	300	5	0.2	C2
520	520	620		2.0	Heating
278	288	230		2.0	Cooling

Cost data

Heating : 80 $/kW,year Cooling : 20 $/kW,year

Annual Area Cost Exchangers ($/year) = 200 x Area

Table 8.2

Tsupply K	Ttarget K	Heat kW	DT-Shift K	U*f kW/K,m²	Descript -
395	343	208	1.0	2.0	H1
405	288	702	14.2	0.2	H2
293	493	1000	0.0	2.0	C1
353	383	300	13.9	0.2	C2
520	520	733		2.0	Heating
278	288	343		2.0	Cooling

Table 8.3

Procedure		Heating kW	Area m^2	Cost \$/year	# units -	# splits -	
Classic Initial load 620 kW	Target	620.0	295.7	113,347	5 - 7	-	
	Tick-off + evolution	725.1	174.6	99,632	6	0	*Fig.8.9*
	LP - Initial network A	620.0	295.7	113,347	11	4	
	After evolution	725.1	174.6	99,632	6	0	*Fig.8.9*
	LP - Initial network B	620.0	295.7	113,347	11	4	
	After evolution	720.1	173.7	98,950	8	1	*Fig.8.5*
Network Yee et al. Initial load 620 kW	Reported network	620.0	263.2	106,834	8	3	
	After evolution	724.0	173.5	99,295	7	1	*Fig.8.7*
Classic Initial load 740 kW	Target	740.0	184.2	103,079	5 - 7	-	
	Tick-off + evolution	725.1	174.6	99,632	6	0	*Fig.8.9*
	LP - Initial network A	740.0	184.4	103,079	11	4	
	After evolution	747.5	171.6	101,274	8	3	
	unwinding splits	724.3	174.7	99,567	7	0	Fig.8.4
	evolution	725.1	174.6	99,632	6	0	*Fig.8.9*
	LP - Initial network B	740.0	184.4	103,079	11	4	
	After evolution	724.0	173.5	99,295	7	1	*Fig.8.7*
	unwinding split	725.1	174.6	99,632	6	0	*Fig.8.9*
Crisscross Initial load 733 kW	Target	733.0	174.8	100,467	5 - 7	-	
	Tick-off + evolution	725.1	174.6	99,632	6	0	Fig.8.9
	LP - Initial network	733.0	171.2	99,747	11	4	
	After evolution	720.1	173.7	98,950	8	1	Fig.8.5
		720.6	173.9	99,033	8	0	Fig.8.6
		724.0	173.5	99,295	7	1	Fig.8.7
		725.4	174.3	99,593	7	0	Fig.8.8
		725.1	174.6	99,632	6	0	Fig.8.9
		929.0	154.4	116,024	5	0	Fig.8.10

Without crisscross, the LP solution is not conclusive for a band with 2 hot steams and 2 cold streams (same area, same cost, independently of the load distribution among the branches); therefore, 2 different subnetworks (A and B) are possible for band 3

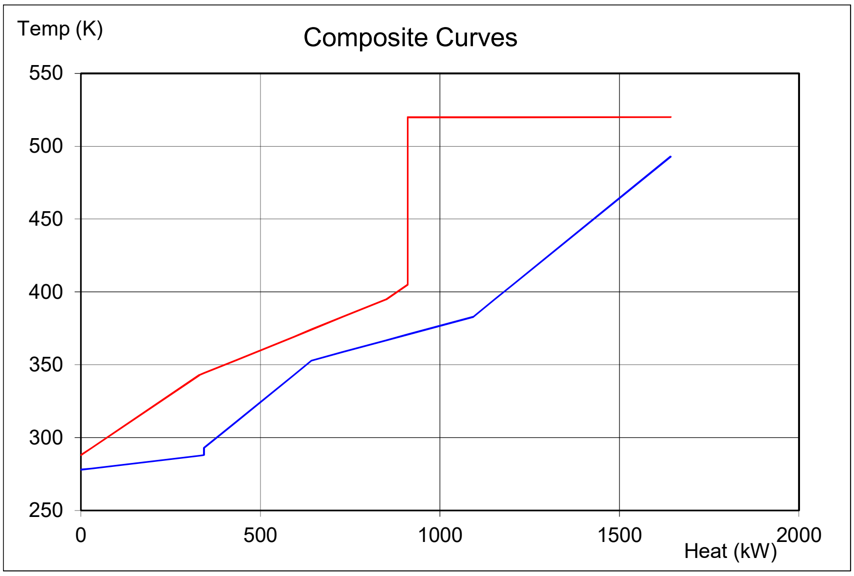


Figure 8.1

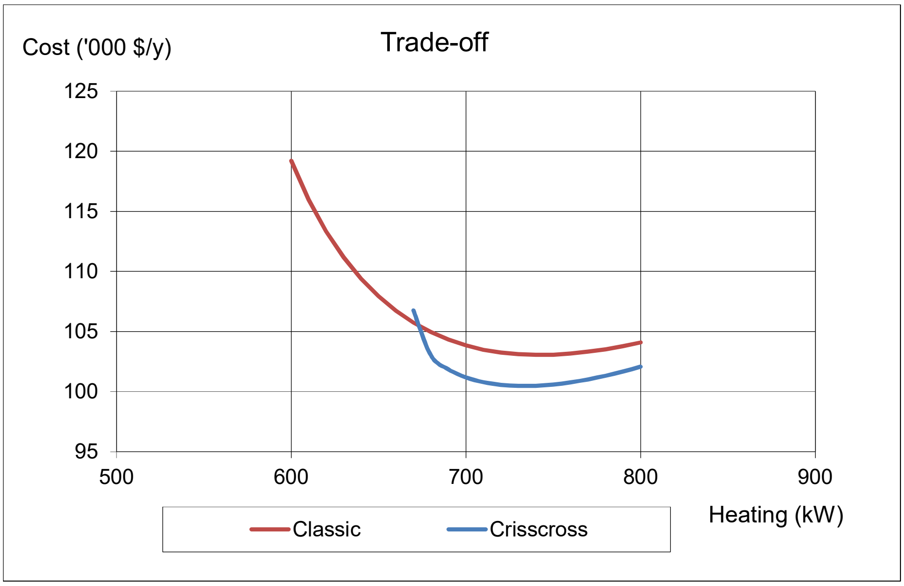
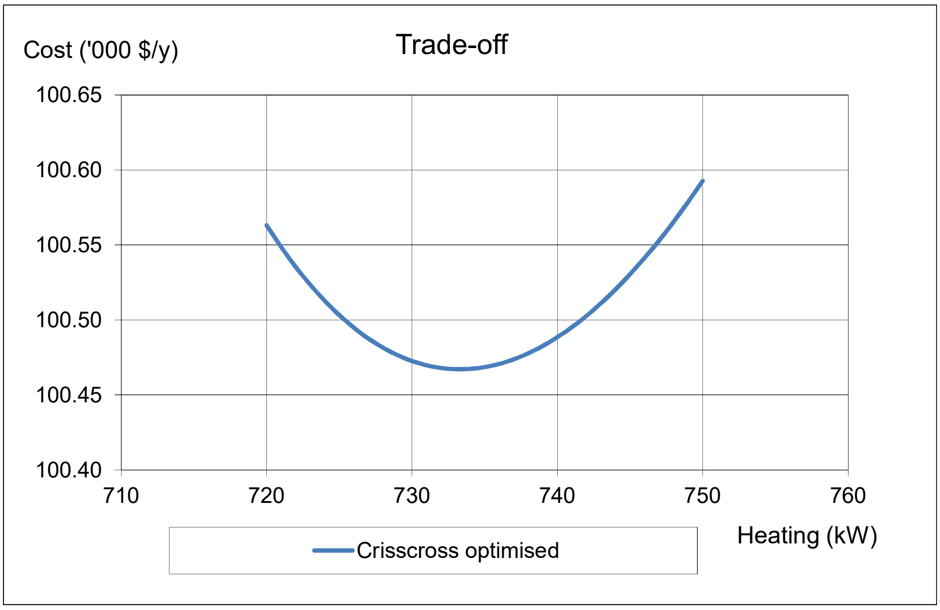


Figure 8.2



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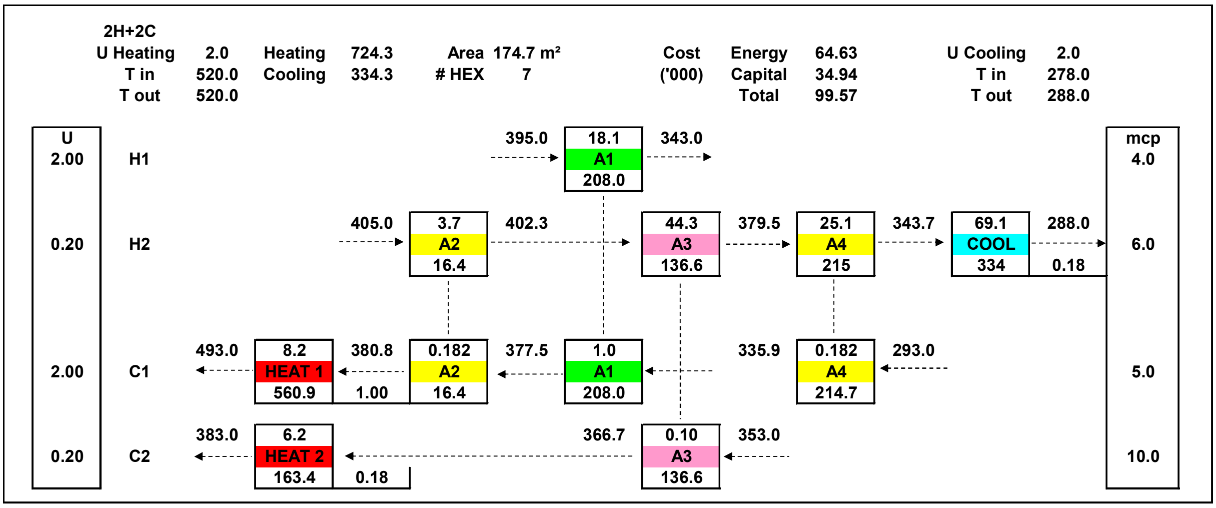

Figure 8.4

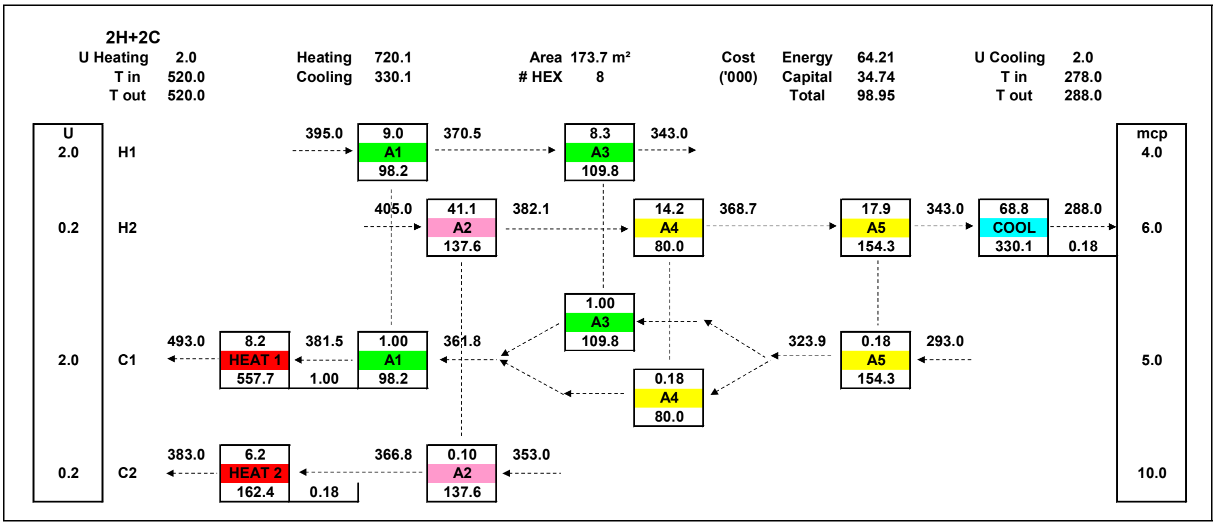

Figure 8.5

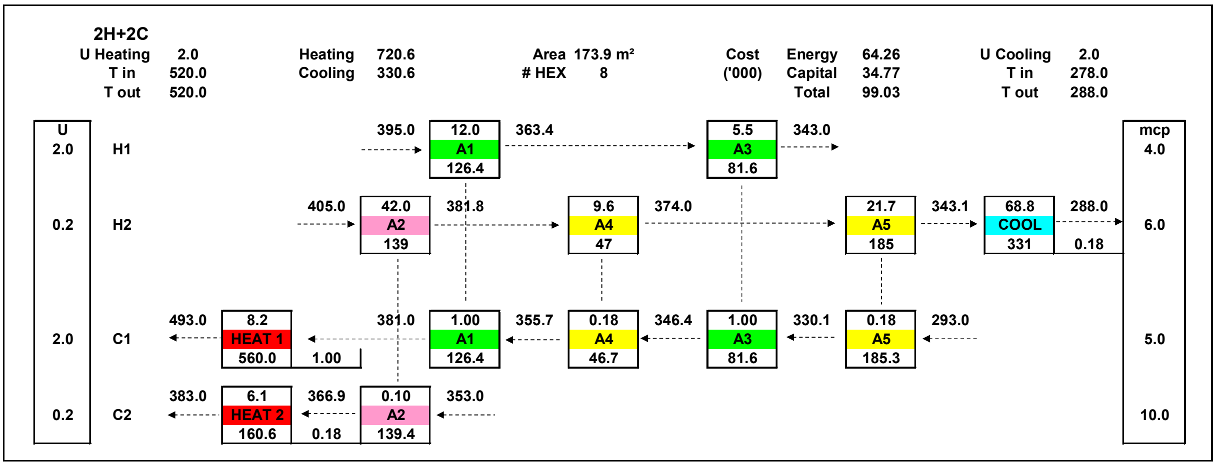

Figure 8.6

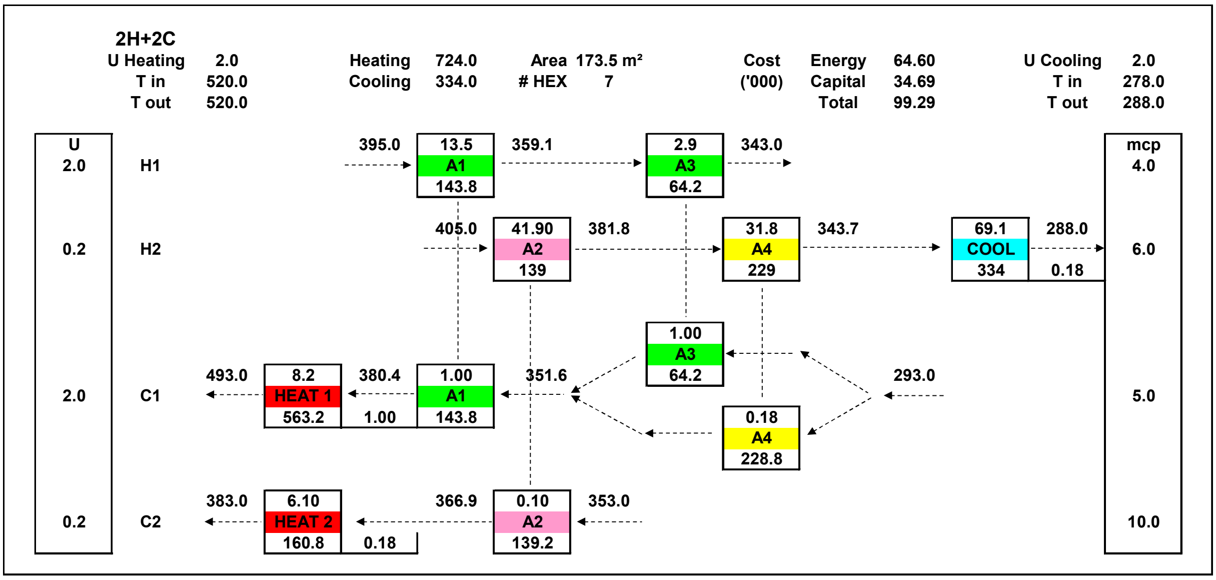

Figure 8.7

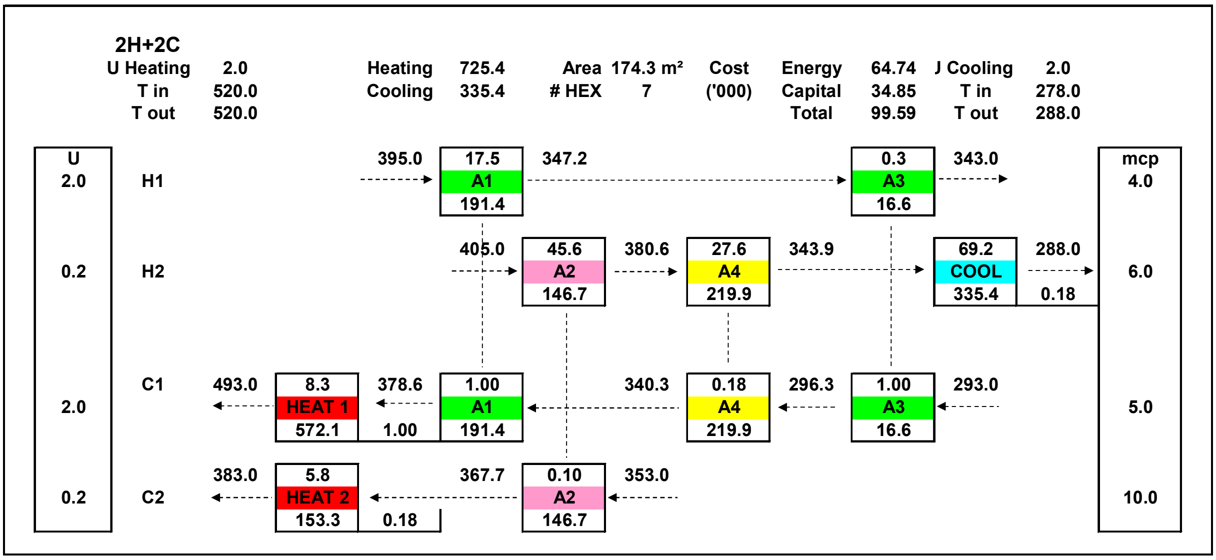

Figure 8.8

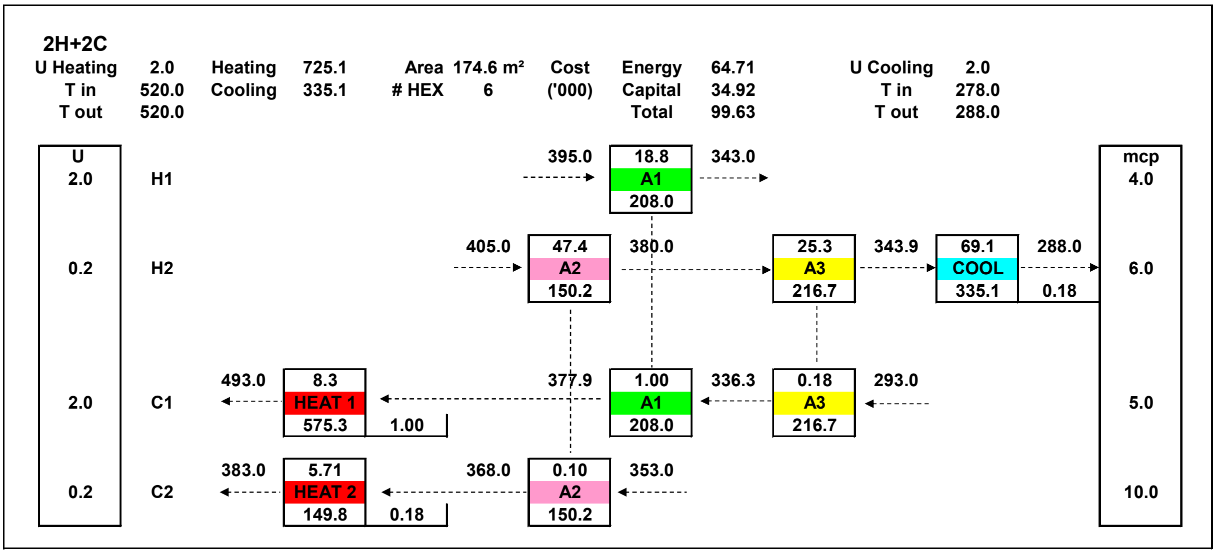

Figure 8.9

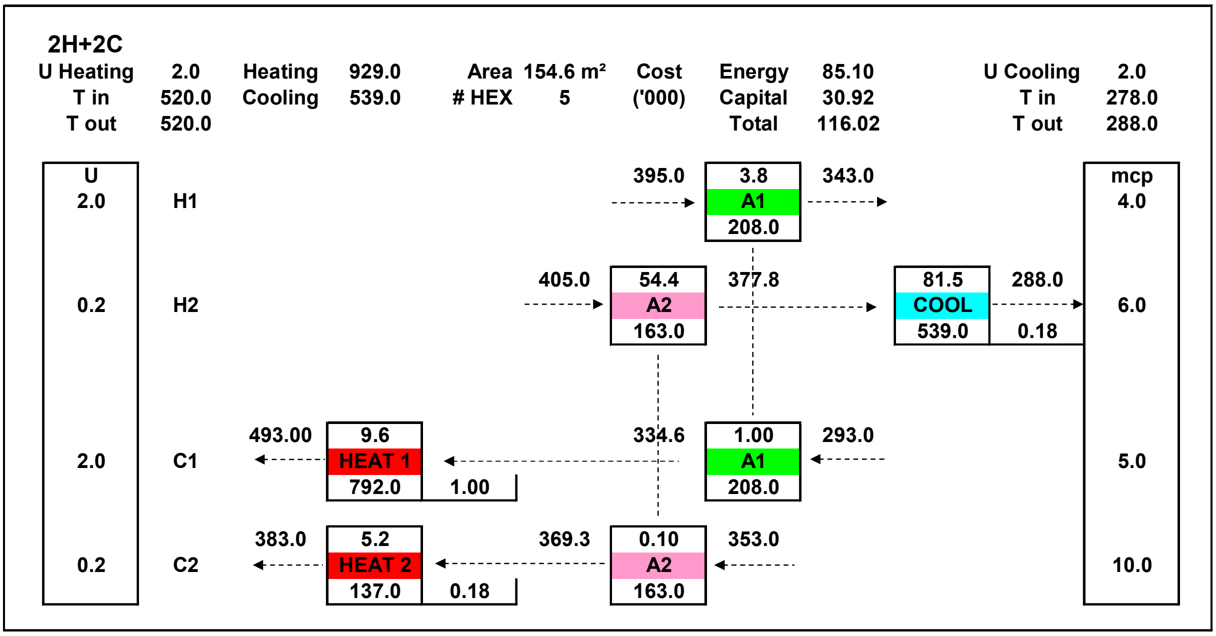

Figure 8.10

9. Example from Gundersen and Grossmann

Example 9 is taken from Gundersen and Grossmann [9.1, 9.2]; it has also been studied by Colberg and Morari [9.3]. The data set is given in Table 9.1. Energy consumption in the table corresponds with an overall DTMin of 20 K.

Composite Curves are shown in Figure 9.1.

In the literature, networks have been reported for minimum investment cost for the stream data as mentioned in Table 9.1, i.e. for a heating load of 1075 kW. However, no trade-off between energy and capital has been studied. In order to enable trade-off, further financial assumptions have been chosen, such that the optimum heating load is in the same range as the proposed value of 1075 kW. Assumed are a lifetime of 5 years and a discount rate of 20%, resulting into an annuity factor of 33.44%. A lifetime of 10 years and a discount rate of 15% would generate an annuity factor of 19.9%, would turn the case into a threshold problem and would seem less appropriate.

With the additional financial assumptions, the trade-off curves in Figure 9.2 indicate an optimum heating value of around 1000 kW. Application of LP on the grid generated by the analysis (Table 9.2) leads to networks with splits as shown in Figure 9.3 and 9.4 (there are 2 alternative load distributions for band 3).

Application of the standard tick-off procedure leads to the networks in Figure 9.5 and Figure 9.6. These networks both have one split. In order to avoid said split, a smart tick-off procedure can be applied by extending the match above the pinch (H1-C1 or H1-C2) to below the pinch until hot stream H1 is fully satisfied. This leads to the best networks as shown in Figure 9.7 (331,995 $/year) and Figure 9.8 (332,556 $/year). The structure of these networks corresponds with the structure of the best network in [9.1], respectively in [9.2], the heat loads, however, are different.

It is also possible to develop networks with the cooler on hot stream H1 instead of on hot stream H2 in a cost range within less than 1% of the optimum. The results are summarised in Table 9.3.

[9.1] T. Gundersen and I. E. Grossmann, Improved Optimization Strategies for Automated Heat Exchanger Network Synthesis through Physical Insights, Computers Chem. Engng, Vol. 14 (1990) No. 9, pp. 925-944.

[9.2] T. F. Yee and I. E. Grossmann, Simultaneous Optimization Models for Heat Integration - II, Engineering Design Research Center, Carnegie Mellon University, March, 1990.

[9.3] R. D. Colberg and M. Morari,Area and Capital Cost Targets for Heat Exchanger Network Synthesis with Constrained Matches and Unequal Heat Transfer Coefficients, Computers chem. Engng, Vol. 14, No. 1. pp. l-22, 1990.

Table 9.1

Tsupply °C	Ttarget °C	Heat kW	DT-Shift K	U*f kW/K,m²	Descript -
150	60	1800	10	0.1	H1
90	60	2400	10	0.1	H2
20	125	2625	10	0.1	C1
25	100	2250	10	0.1	C2
180	180	1075		0.1	Heating
10	15	400		0.1	Cooling

Cost data

Heating : 80 \$/kW,year Cooling : 20 \$/kW,year

Cost Exchangers (\$) = 8600 + 670 x Area$^{0.83}$

Annuity 33.44%

Annual Cost Exchangers (\$) = 2875.7 + 224 x Area$^{0.83}$

Table 9.2

Band		1	2	3	4	5
DeltaT	55.0	88.2	20.0	40.3	44.0	50.0
Heating	180.0	180.0				
H1		150.0	90.0	65.3	64.0	60.0
H2			90.0	65.3	64.0	60.0
C1	125.0	91.8	70.0	25.0	20.0	
C2	100.0	91.8	70.0	25.0		
Cooling					15.0	10.0

Table 9.3

Results	Heating kW	Area m²	Cost '000 \$/year	# units	# splits
Cooler on H2					
Linear Programming A	1178	2962	335.96	5	2
Linear Programming B	999	3094	335.93	6	2
Tick-off A	1170	2951	332.65	5	1
Tick-off B	990	3241	334.32	6	1
Smart tick-off A	1157	2951	332.00	5	0
Smart tick-off B	969	3238	332.56	6	0
Cooler on H1					
Tick-off A	977	3160	333.44	6	1
Tick-off B	874	3436	335.02	6	0

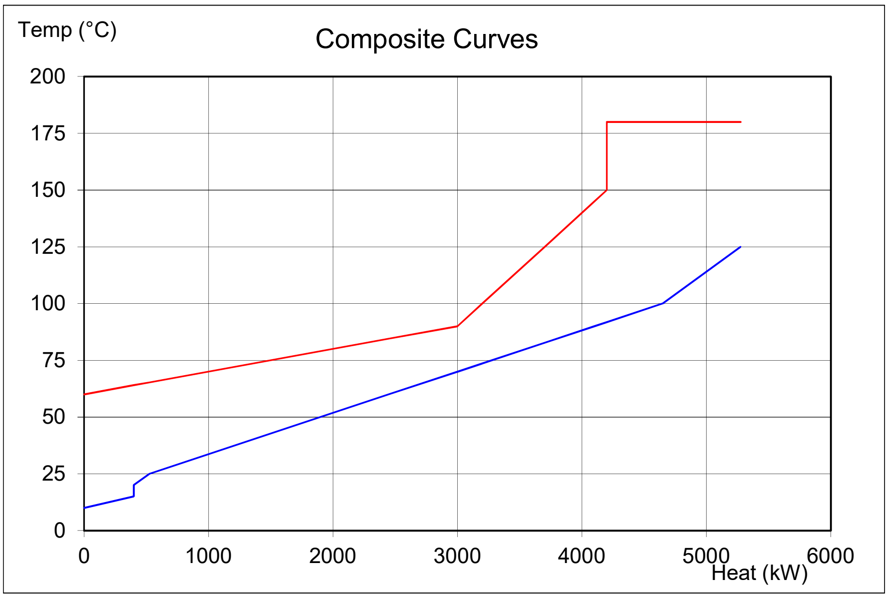

Figure 9.1

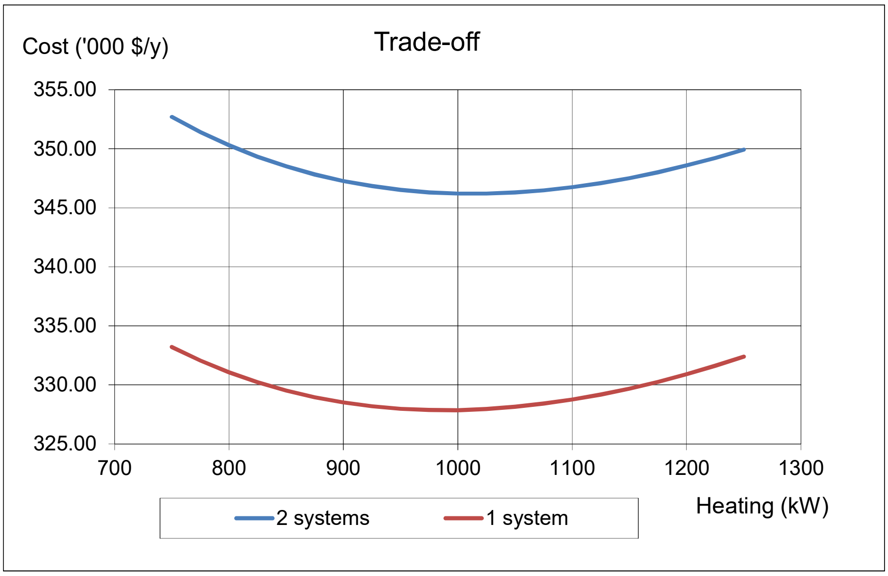

Figure 9.2

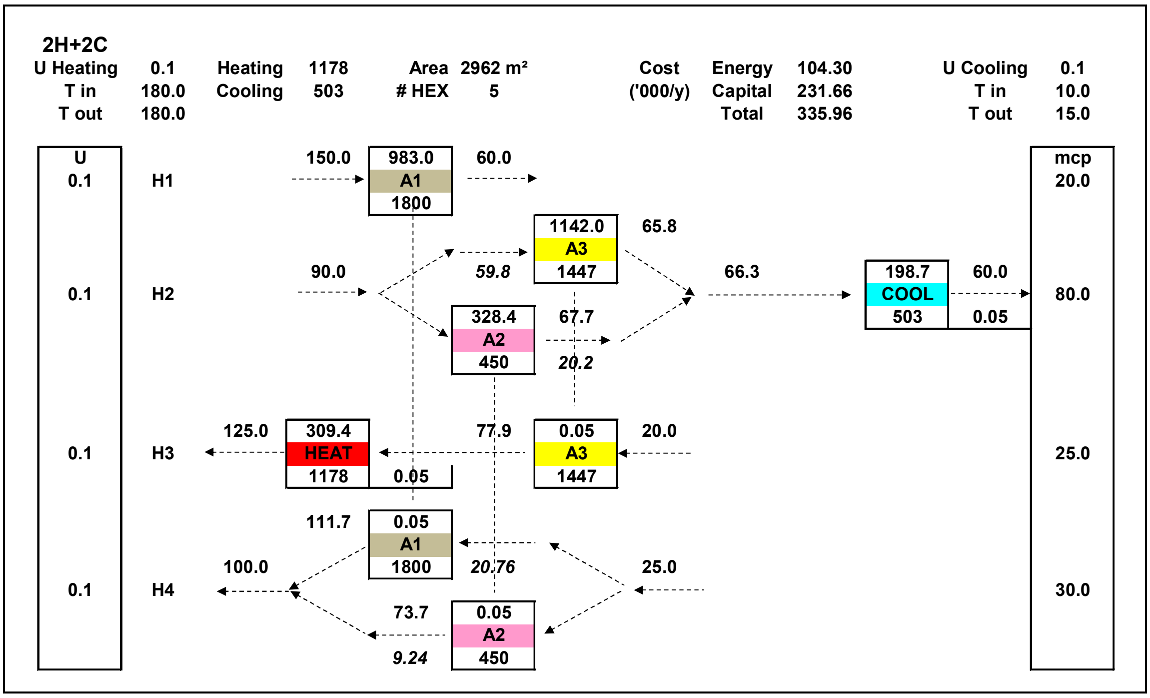

Figure 9.3

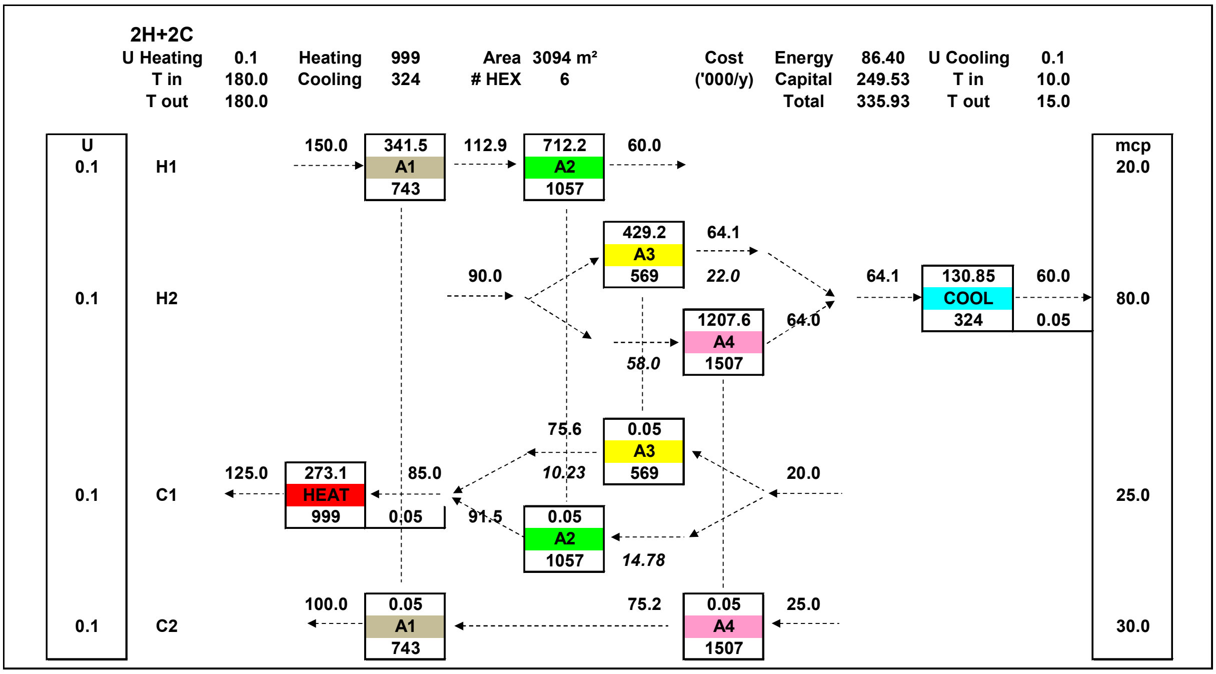

Figure 9.4

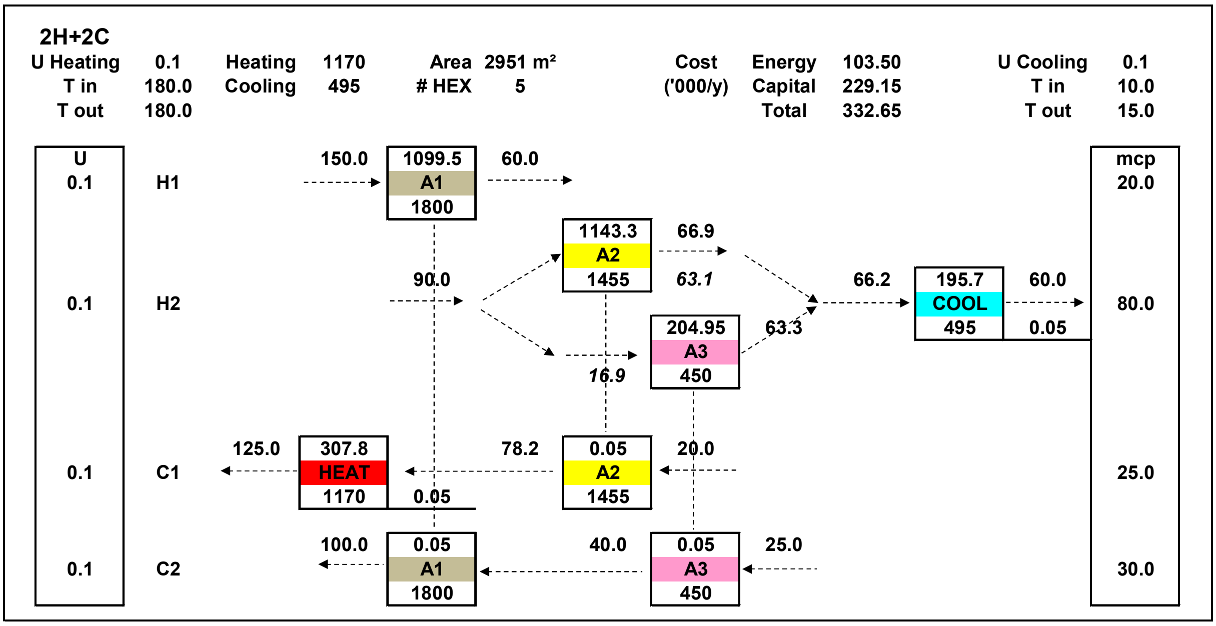

Figure 9.5

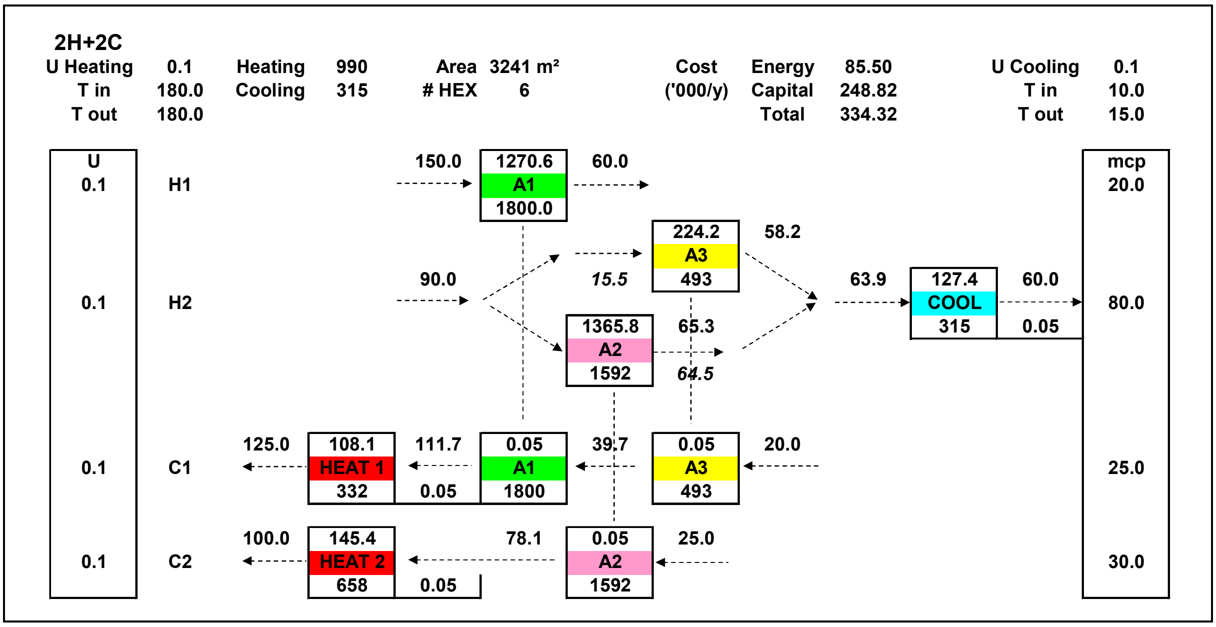

Figure 9.6

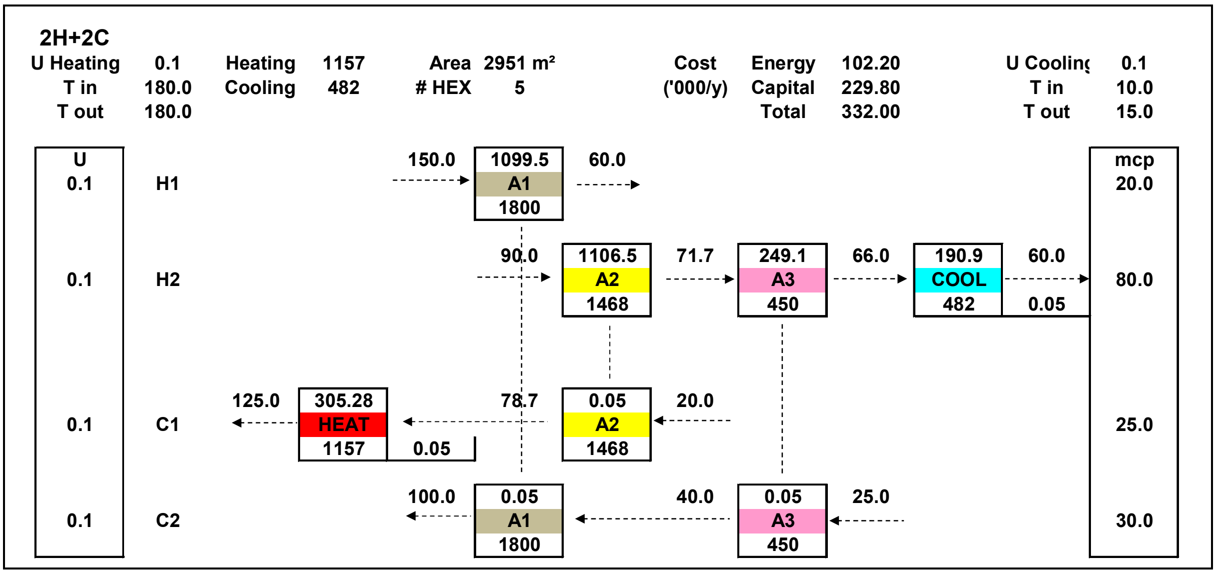

Figure 9.7

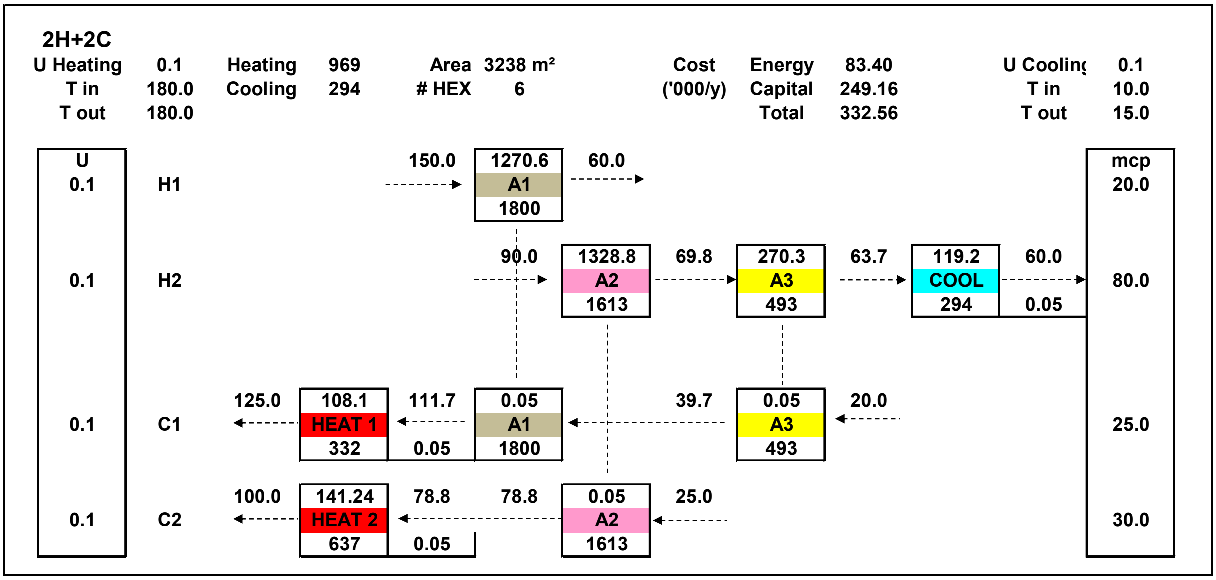

Figure 9.8

10. Example from Ponce-Ortega

Example 10 is an example originally from Gundersen and Grossmann [10.1] and it has been analysed here before as example 9. It was adapted by Ponce-Ortega [10.2] who used different heat transfer values, different cost data and introduced intermediate utilities.

The data set is given in Table 10.1. Composite curves are shown in Figure 10.1. Shift values in Table 10.1 have been optimised for the given heat load of 1180 kW, set according to the minimum in the trade-off curves in Figure 10.2.

Area targets are 1641 m² with classic pinch analysis and 1586 m² with crisscross; cost targets are 375,549$/year with classic pinch analysis and 372,909 $/year with crisscross.

The grid from classic pinch analysis would put the heater(s) intermediate due to the temperature level of the steam as also can be seen in the Composite Curves. Crisscross optimisation, however, will move the heater(s) upfront due to the better heat transfer coefficient of the steam.

Various methods can be used to synthesis the networks. The most interesting results are shown in Table 10.2 and the corresponding networks in Figure 10.3 to Figure 10.5. With a cost of 375,536 $/year for the best network, the cost target can be met, albeit with more energy and less capital.

[10.1] Gundersen T. and I. E. Grossmann; Improved optimization strategies for automated heat exchanger network synthesis through physical insights. Paper presented at AIChE, Ann1 Mtg, Washington, D.C. (1988).

[10.2] José M. Ponce-Ortega, Medardo Serna-Gonzàlez, Arturo Jiménez-Gutiérrez; Synthesis of Heat Exchanger Networks with Optimal Placement of Multiple Utilities, Ind. Eng. Chem. Res. 2010, 49, 2849–2856

Table 10.1: Data set example 10

Tsupply K	Ttarget K	Heat kW	Shift K	U*f kW/m²,K	Description -
423	333	1800	10	0.10	H1
363	333	2400	3	0.20	H2
293	398	2625	2	0.20	C1
298	373	2250	0	0.30	C2
410	410	1180	-4	2.50	Heating
293	323	505	0	1.00	Cooling

Heating : 80.0 $/kW,yearCooling : 15.0 $/kW,year
HEX cost ($/year) = 5500 + 150 x Area

Table 10.2: Networks, results.

Networks	Heating kW	Area m²	# units -	# splits -	Cost $/year
Minimum cost	1296	1567	5	1	375,536
Minimum cost without splits	1278	1563	6	0	378,683
Minimum cost and minimum units without splits	1541	1447	5	0	380,751

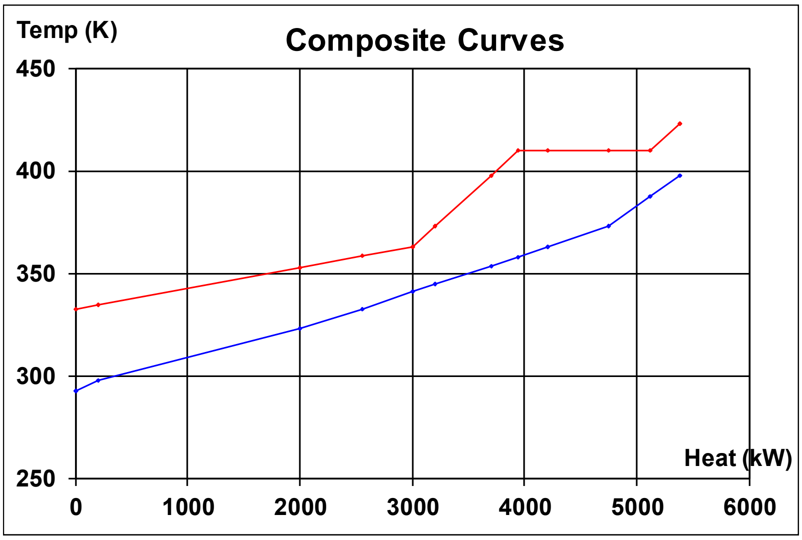

Figure 10.1: Composite Curves.

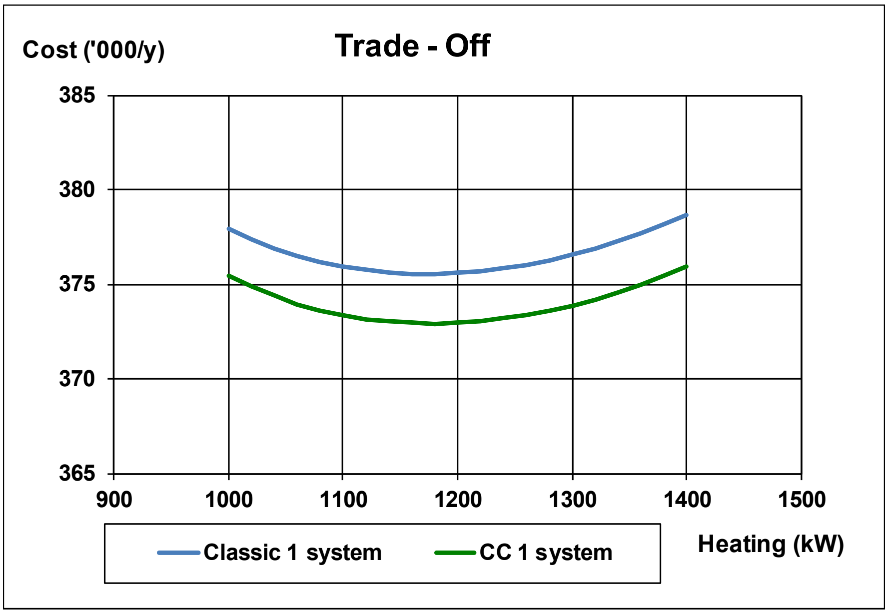

Figure 10.2: Trade-Off Energy versus Capital.

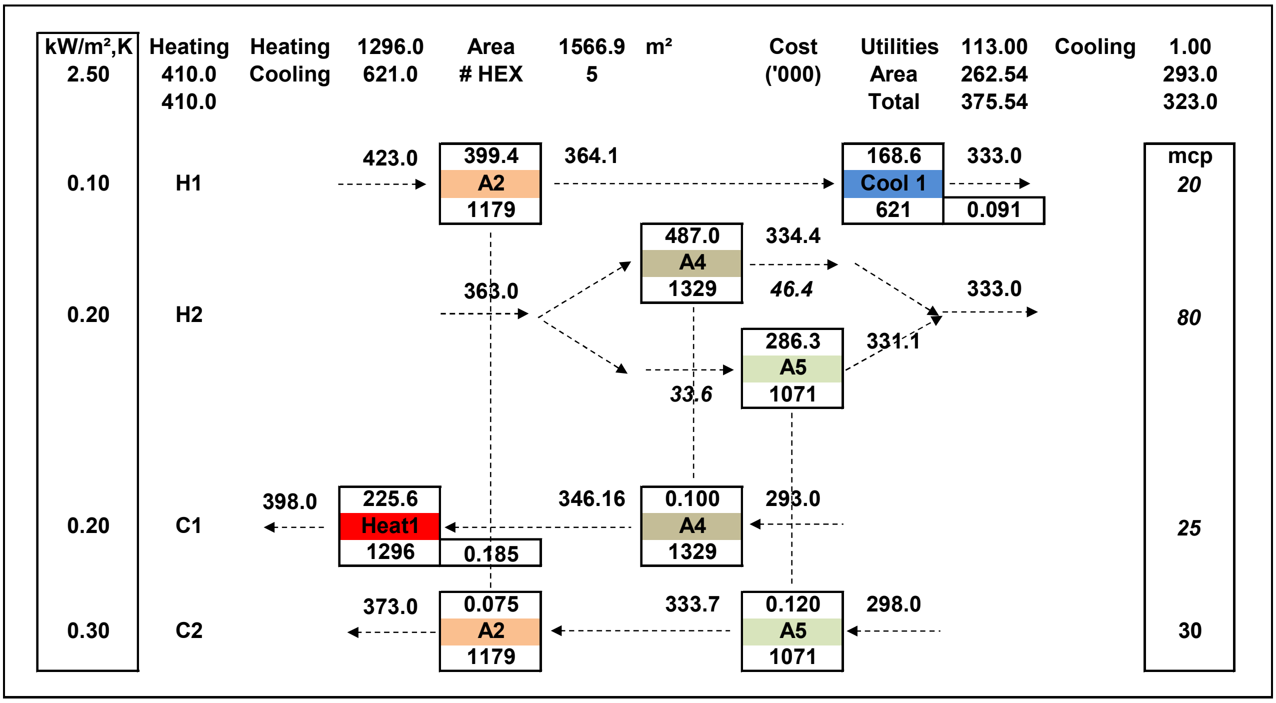

Figure 10.3: Network for minimum cost.

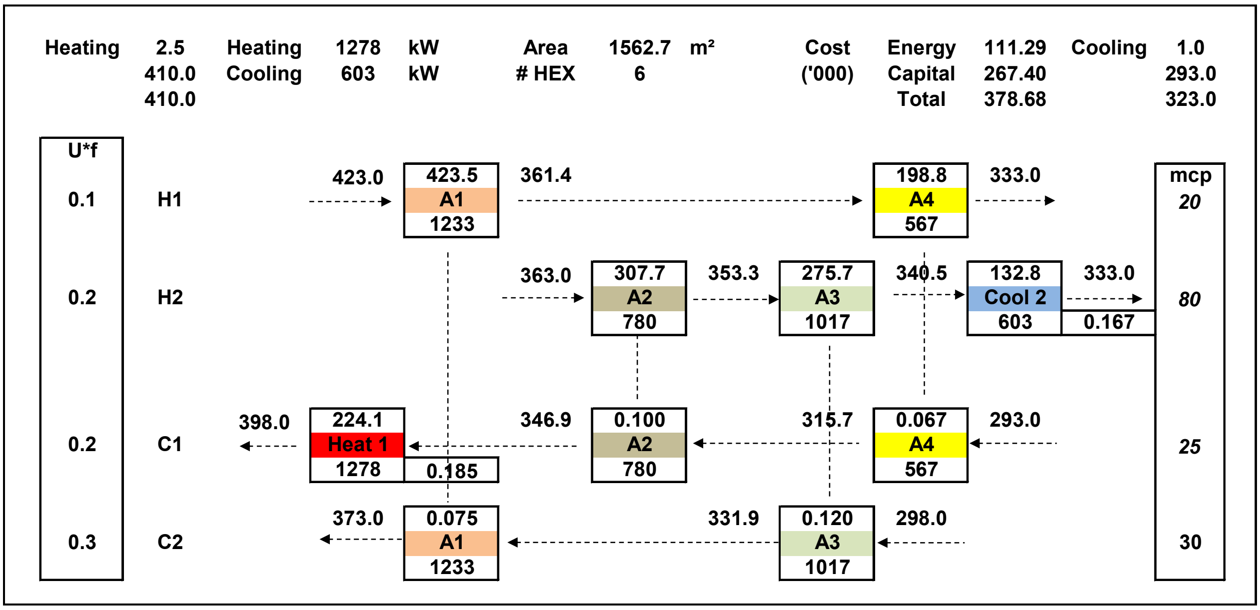

Figure 10.4: Network for minimum cost without splits.

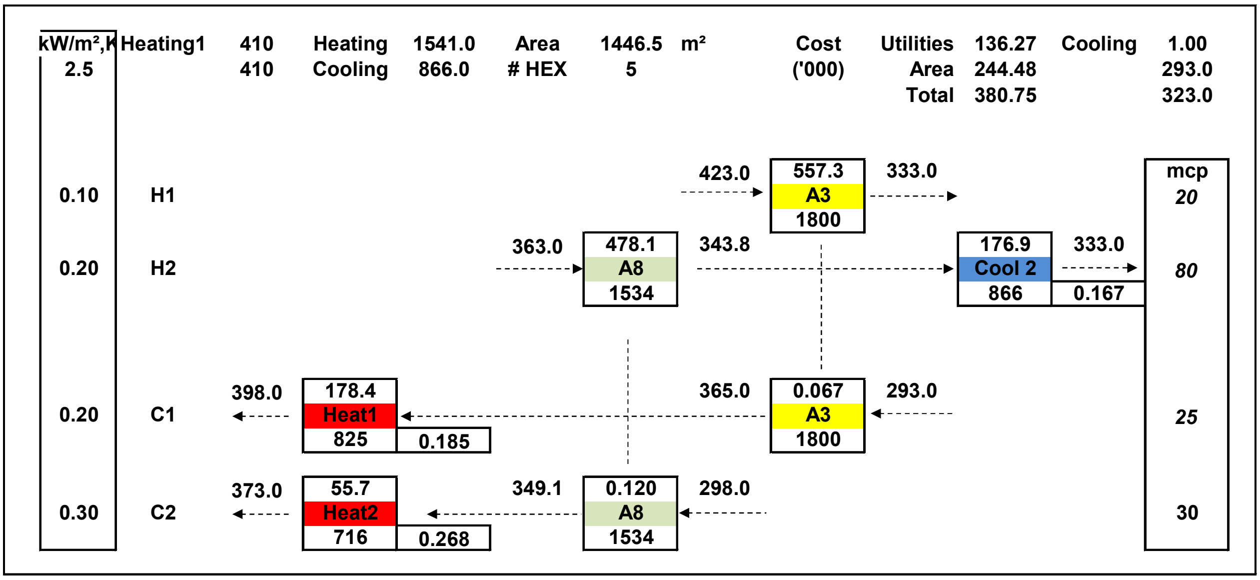

Figure 10.5: Network for minimum cost and minimum units without splits.

11. Example from Ahmad, Nielsen & Khorasany

Example 11, originally from Ahmad (1985), was further treated by Nielsen and by Khorasany et al. The data set is given in Table 11.1 with cost data from Nielsen. Energy consumption in the table corresponds with an overall DTMin of 10 K.

Composite Curves are shown in Figure 11.1.

The objective is to design a network with shell-and-tube 1/2 exchangers which might require units with multiple shells, each of them subject to the applicable cost formula. Expectedly, the minimum number of shells will be larger than the minimum number of units and each shell will be subject to a Ft factor which will have an impact on the cost and the trade-off procedure.

Trade--off without taking into account a Ft factor leads to the curves in Figure 11.2; the optimum is around a heating load of 25 kW. Application of the tick-off procedure and optimisation leads to the network of Figure 11.4; the result can be compared with the cost of published networks in Table 11.2

In order to anticipate the effect of a Ft factor for trade-off prior to design, a Ft value of 0.85 was assumed for all exchangers. Further, as a rough first estimate, the number of shells was set at twice the minimum number of units and the resulting surface area per shell for a heating load at the optimum was chosen as a maximum surface area per shell. The resulting trade-off curve is shown in Figure 11.3; it suggests an optimum heating load of around 50 kW in case of 1 system and around 65 kW if segregation at the pinch is considered.

Application of the tick-off procedure with a heating load of 50 kW or 65 kW followed by incremental evolution leads to the optimum network of Figure 11.8 with 7 units, 14 shells and a cost of 19,041 $/year. Distortion of the solution space and optimisation leads to the network of Figure 11.9 with 6 units, 13 shells and a cost of 19,119 $/year.

Application of LP on the grid from the analysis with a heating load of 50 kW or less leads to the network of Figure 11.10 with a cost of 19,084 $/year. Application of LP on the grid from the analysis with a heating load of 54 kW or more leads to the network of Figure 11.11 with a cost of 19,154 $/year.

The last cost figures apply for isothermal splits, the effect of non-isothermal splits is negligible. There are a number of sub-optimal solutions within a cost range of less than 0.2% from the optimum.

The results are summarised in Table 11.2.

[11.1] Ahmad S., Heat Exchanger Networks: Cost Trade-Offs in Energy and Capital, Ph.D. Thesis, UMIST, Manchester, UK (1985).

[11.2] Jan Sandvig Nielsen, Mogens Weel Hansen and Sten bay Joergensen, Heat Exchanger Network Modelling Framework for Optimal Design and Retrofitting, Computers chem. Engng Vol. 20 1996), Suppl., pp. S249-S254

[11.3] R.M. Khorasany, M. Fesanghary, A novel approach for synthesis of cost-optimal heat exchanger networks, Computers chem. Engng Vol.33 (2009), pp. 1363–1370.

Table 11.1

Tsupply °C	Ttarget °C	Heat kW	DT-Shift K	U kW/K,m²	Descript °C
260	160	300		0.4	H1
250	130	180		0.4	H2
120	235	230		0.4	C1
180	240	240		0.4	C2
280	279	50		0.4	Heating
30	80	60		0.4	Cooling

Cost data

Heating : 110 /kW,year Cooling : 12.2 /kW,year

Area Cost ($/year) = 300 x $\text{Area}^{0.5}$

Table 11.2

HEN with countercurrent heat exchange

Author	Heating kW	Area m²	# units -	# splits -	Cost $/year	
Ahmad	50.0	127.2	7	0	13,967	
Nielsen	34.0	159.0	8	0	12,971	
Khorasany	18.1	237.0	7	0	11,816	
Declercq	18.1	242.5	7	0	11,540	Fig.10.4

HEN with Shell-and-tube 1/2 heat exchangers

Ft factor >= 0.8

Author	Heating kW	Installed m²	# units -	# shells -	# splits -	Cost $/year	
Ahmad	50.0	142.3	7	15	0	19,640	Fig.10.5
Nielsen	34.0	189.5	8	17	0	20,407	Fig.10.6
Khorasany	18.1	278.3	7	23	0	25,452	Fig.10.7
Declercq	47.5	153.9	7	14	0	19,041	Fig.10.8
	54.7	142.7	6	13	0	19,119	Fig.10.9
	49.3	151.1	7	14	1	19,084	Fig.10.10
	48.8	149.3	7	14	1	19,154	Fig.10.11

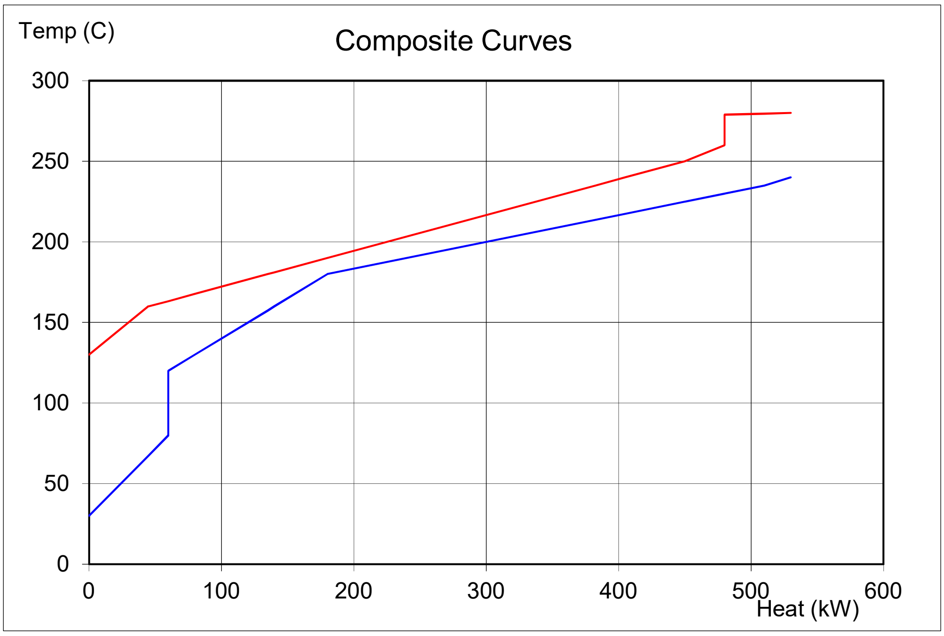

Figure 11.1

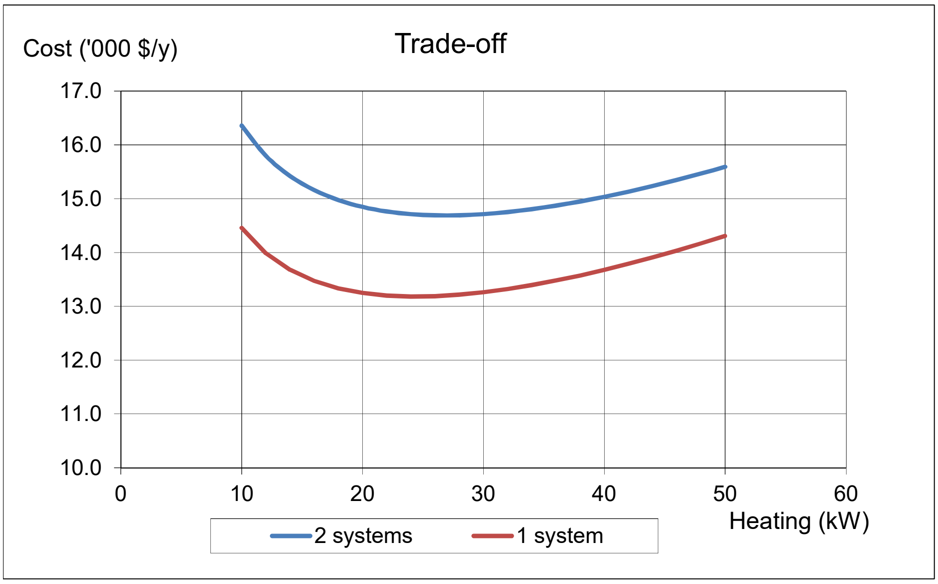

Figure 11.2

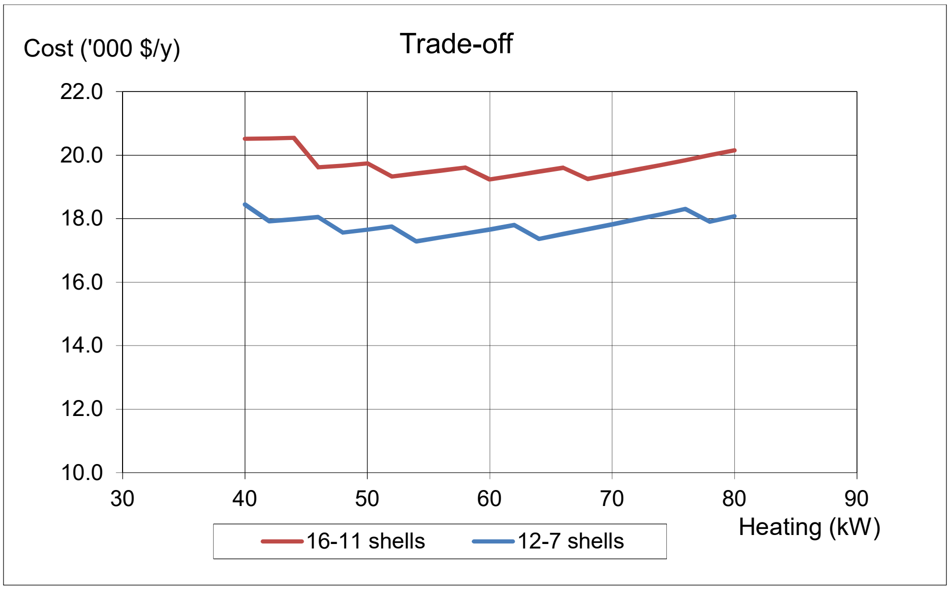

Figure 11.3

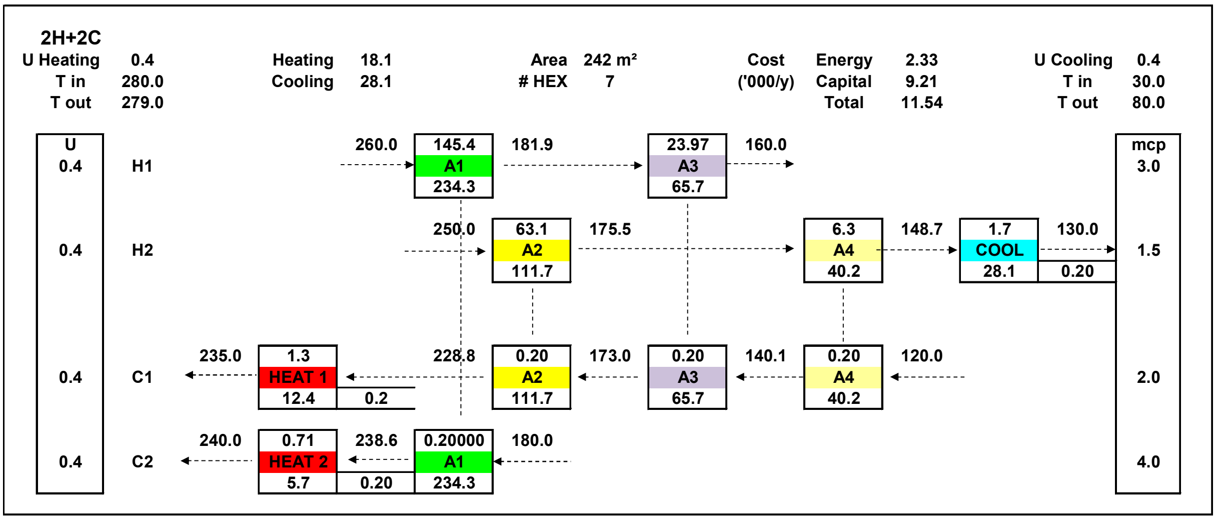

Figure 11.4

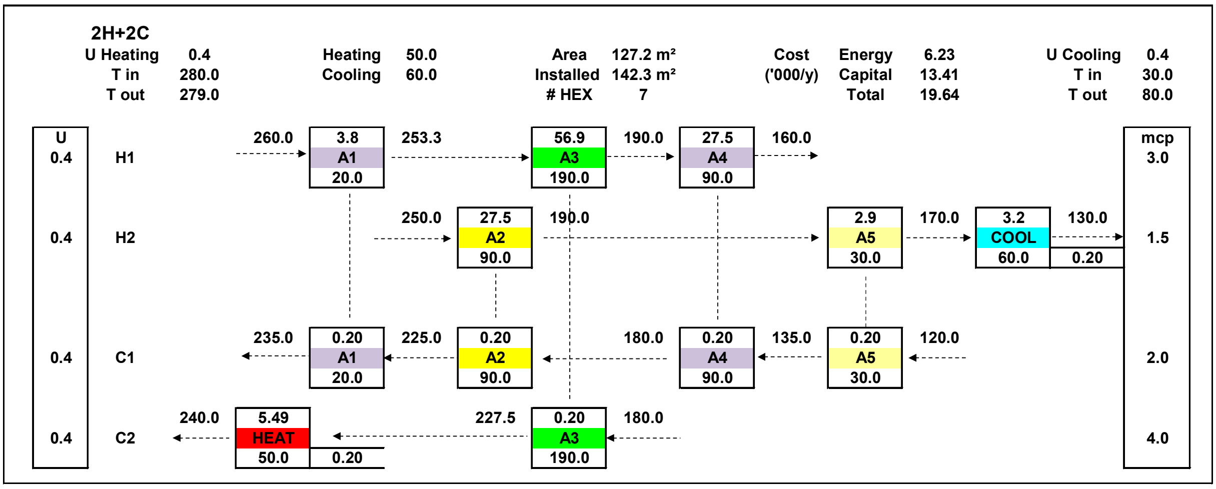

Figure 11.5

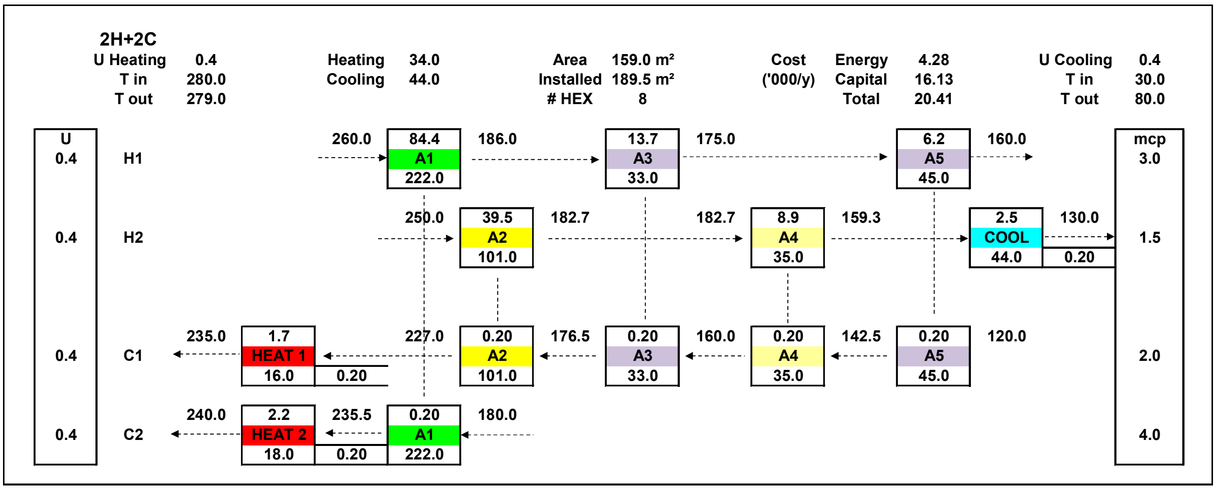

Figure 11.6

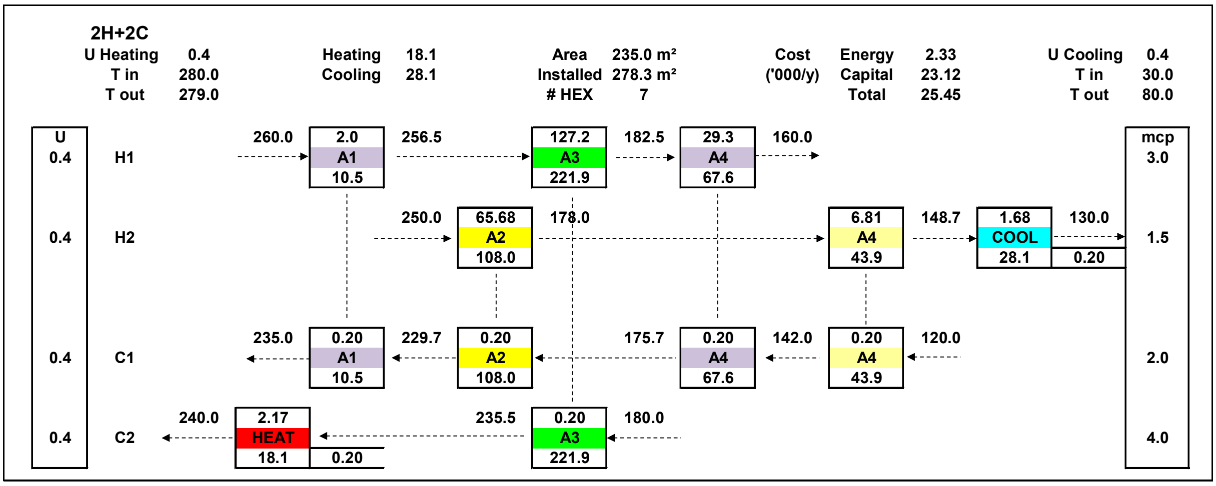

Figure 11.7

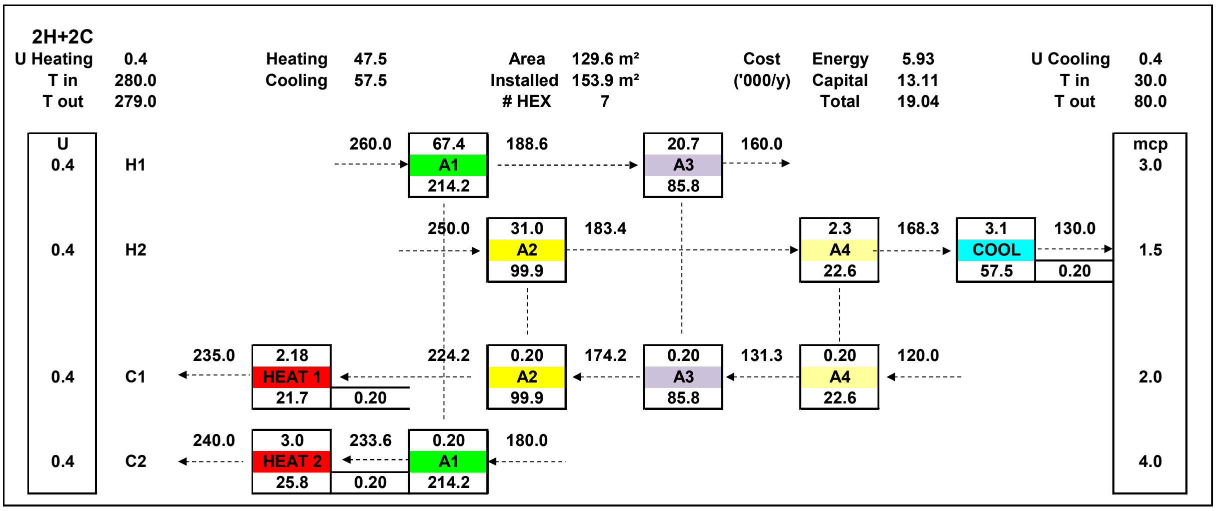

Figure 11.8

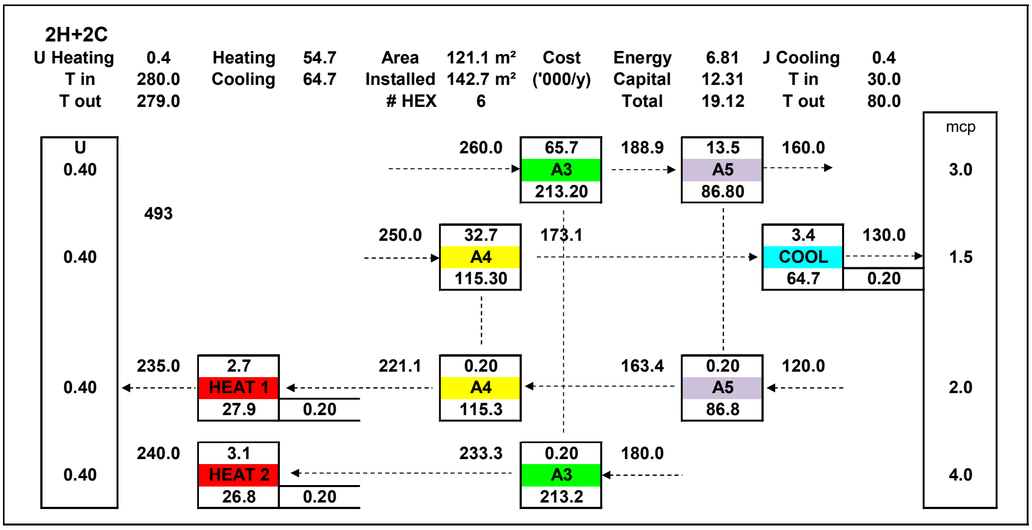

Figure 11.9

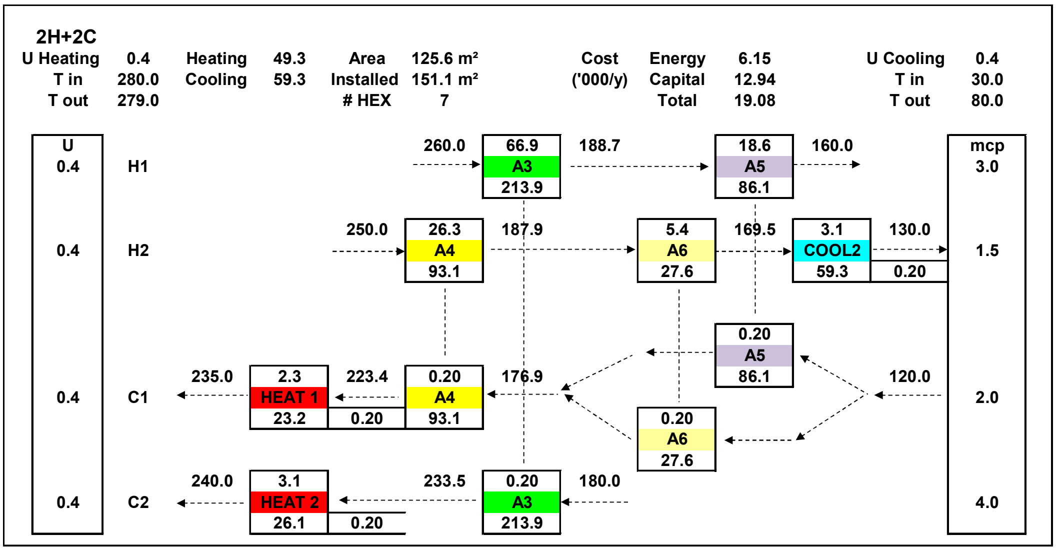

Figure 11.10

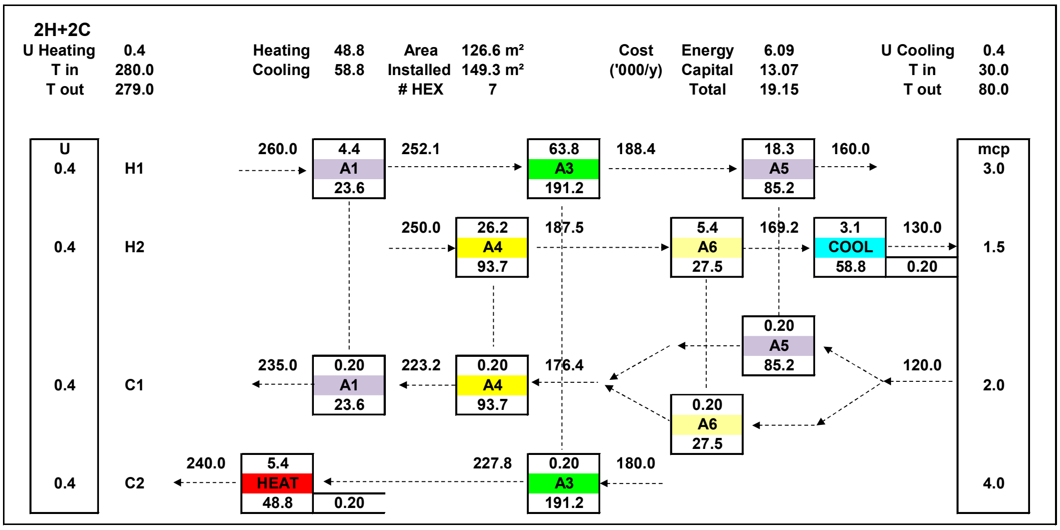

Figure 11.11

12. Example from Björk & Westerlund

Example 12 is from Björk & Westerlund [12.1], also treated by Laukkanen [12.2]. The data set is given in Table 12.1 with Composite Curves as shown in Figure 12.1. Energy consumption in the table corresponds with an overall DTMin of 5 K, as suggested by the trade-off curves in Figure 12.2; Since the area cost for Heaters is different from that of other exchangers and the final number of Heaters is unknown at the targeting stage, targeted area cost depends not only upon the assumed number of units, but also upon the assumed number of Heaters. Minimum and maximum target values are therefore shown in Figure 12.3. For the targeted heating, the area is 9170 m² and cost is between 400,000 and 442,000 $/year.

In Table 12.1, also small shift values are shown for the streams with the lowest heat transfer coefficients; the impact thereof, however, is negligible (reduction of only 0.1% on the area target) and these shift values will further be disregarded.

Following pinch design rules, a tick-off procedure can be applied with 2 Heaters or, alternatively, with one Heater. This leads after evolution to the networks as shown in Figure 12.3, respectively Figure 12.4. Unwinding the splits in these networks reduces the cost further as shown in Figure 12.5 for the last one.

Also the use of heuristic rules (tick-off biggest but one against the biggest stream; match streams with comparable mcp's that are spanning the pinch) whilst respecting the minimum DeltaT of 5 K is applicable; this leads to the network in Figure 12.6.

Finally, application of LP to the grid from the analysis leads to the network in Figure 12.7 and, after unwinding the remaining split, to the optimum network with 6 units and a cost of 421,785 $/year as shown in Figure 12.8.

The results are summarised in Table 12.2.

[12.1] K.-M. Björk, T. Westerlund, Global optimization of heat exchanger network synthesis problems with and without the isothermal mixing assumption, Computers and Chemical Engineering 26 (2002) 1581-1593

[12.2] T. P. Laukkanen, Multi-objective Heat Exchanger Network Synthesis Based on Grouping of Process Streams. Doctoral Dissertations 83/2012, Aalto University publication series.

Table 12.1

Tsupply °C	Ttarget °C	Heat kW	Shift K	U*f kW/m²,K	Description -
180	75	3150	0	0.15	H1
240	60	7200	2	0.10	H2
40	230	6650	0	0.20	C1
120	300	3600	2	0.10	C2
325	325	2025	0	2.00	Heating
25	40	2125	0	0.50	Cooling

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

HEX and Cooler cost ($/year) = 15000 + 30 x Area$^{0.8}$

Heater cost ($/year) = 15000 + 60 x Area$^{0.8}$

Table 12.2

Procedure	Heating kW	Area m^2	Cost $/year	# units	# splits	Ref.
Targeting	2025	10,345	441,616	7 (2 Heaters)		
			399,886	5 (1 Heater)		
Design						
Tick-off with 2 Heaters	2025	11,921	440,491	8	1	
evolution	1983	12,648	438,596	8	1	Fig.11.3
Tick-off with 1 Heater	2025	12,909	428,890	7	1	
evolution	1983	13,474	427,047	7	1	Fig.11.4
after unwinding split	2007	12,766	425,682	7	0	Fig.11.5
Heuristics	2500	7,459	425,759	5	0	
evolution	2439	8,301	422,826	5	0	Fig.11.6
LP - initial network	2025	10,348	470,672	13	4	
evolution	1983	12,636	426,242	7	1	Fig.11.7
after unwinding split	2175	11,398	421,785	6	0	Fig.11.8
Published results						
Björk and Westerlund	1915	16,223	436.367 °)	6	1	
	1966	16,477	442.815 °)	6	0	
Laukkanen	2457	7,952	423.207 °°)	5	0	
	2443	8,094	424.699	5	0	

°) recalculated

°°) network as in Fig.11.6 but not fine tuned

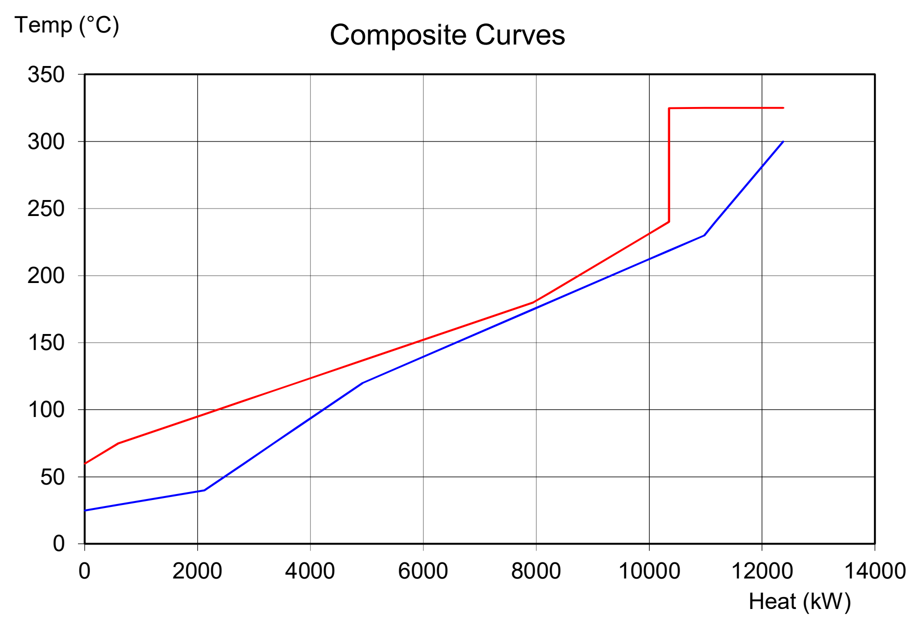

Figure 12.1

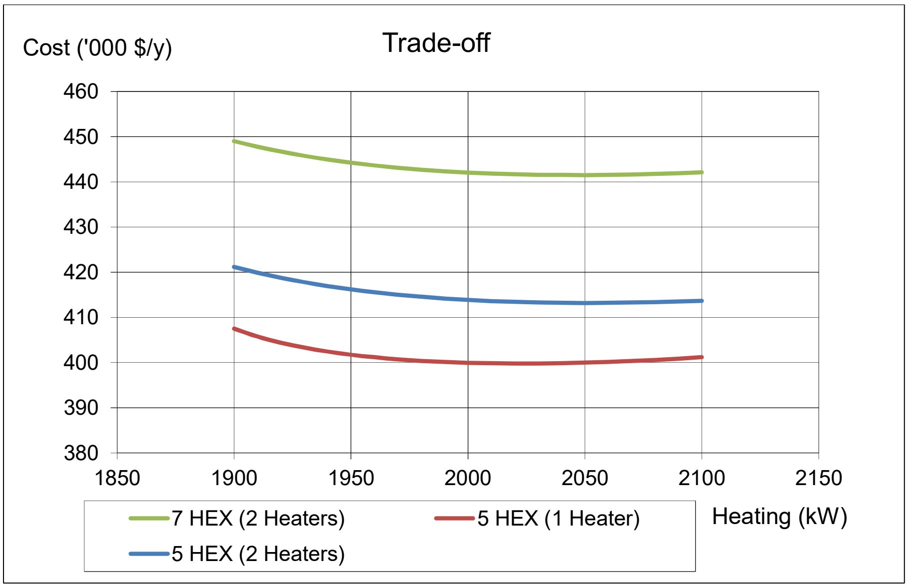

Figure 12.2

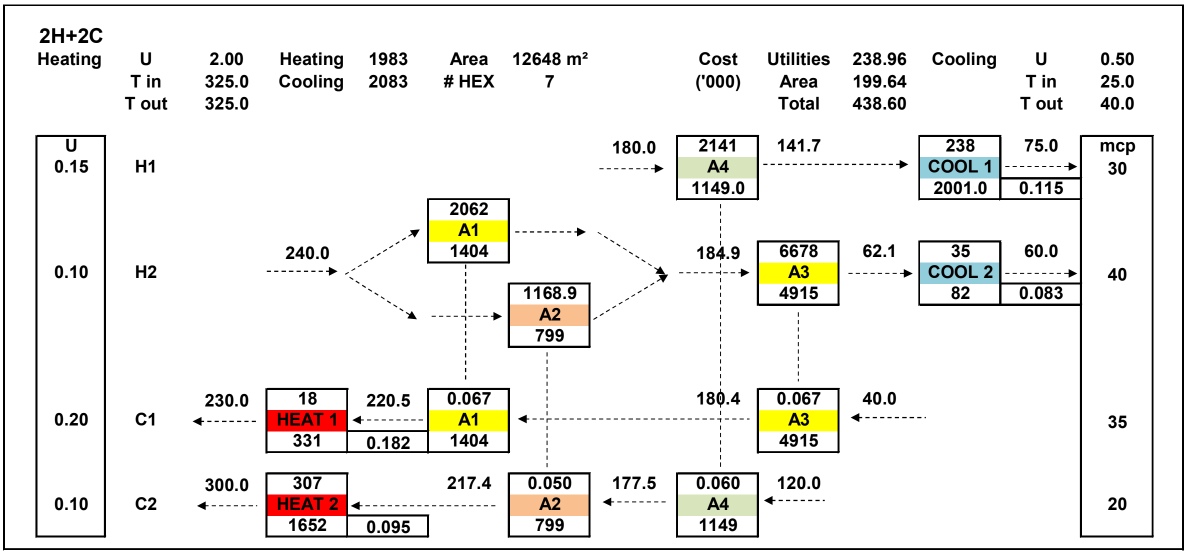

Figure 12.3

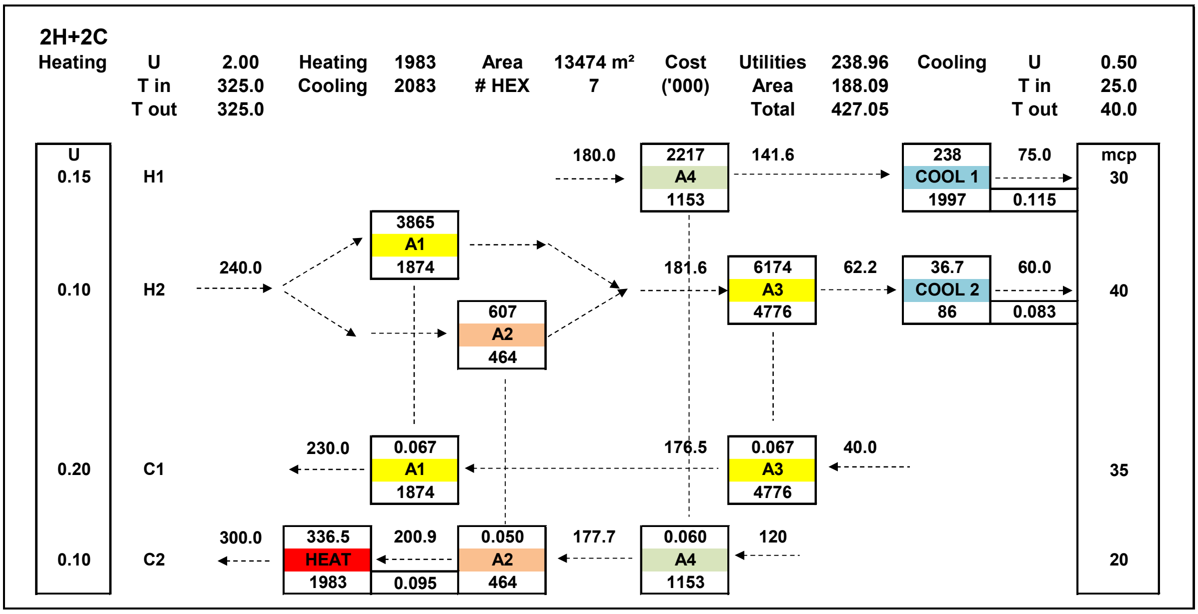

Figure 12.4

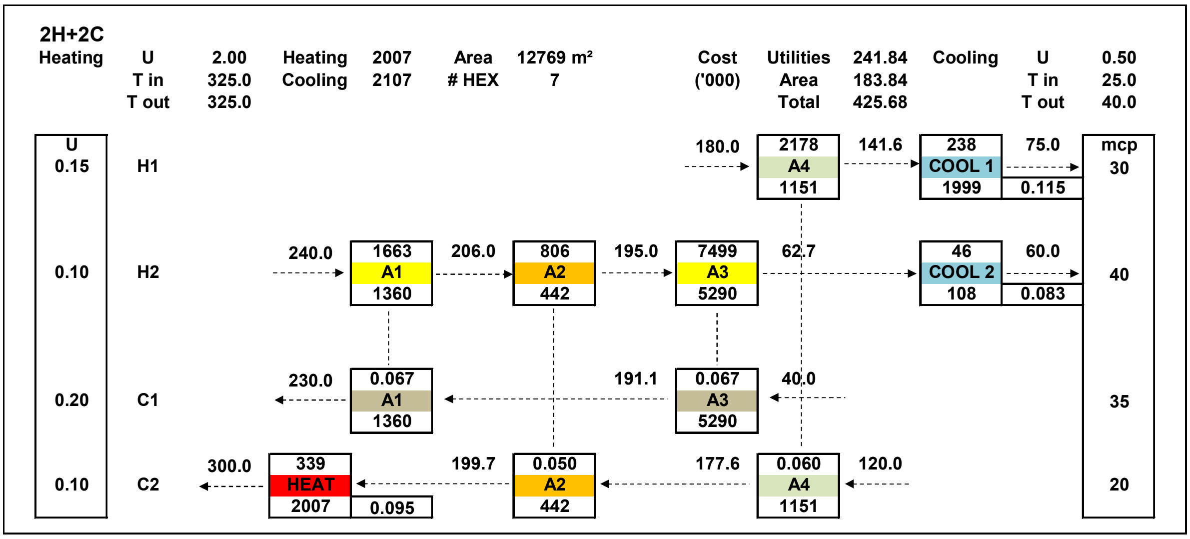

Figure 12.5

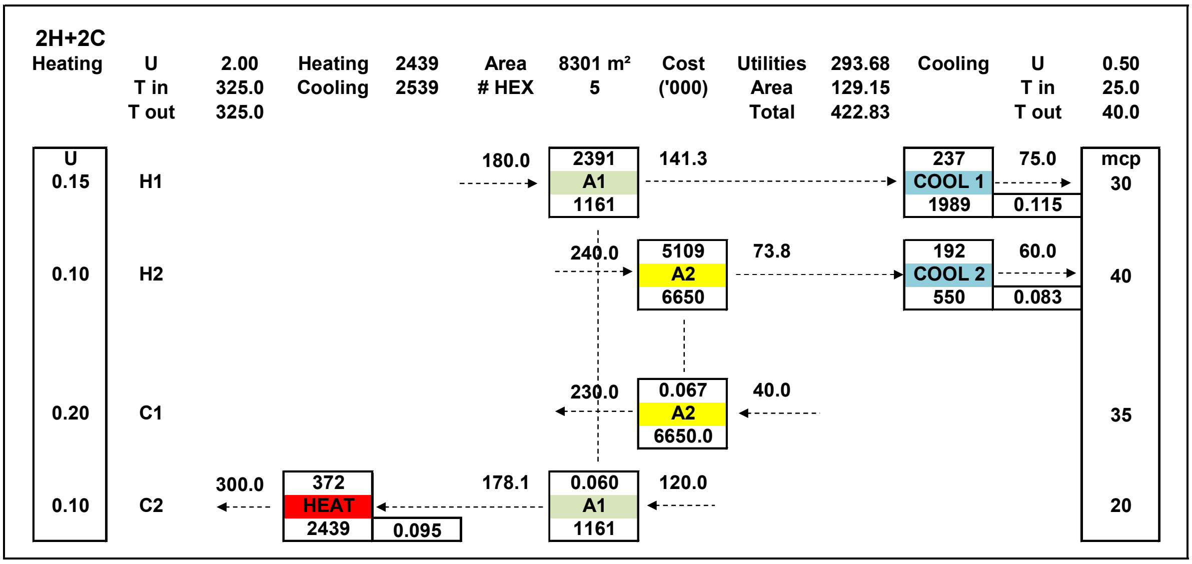

Figure 12.6

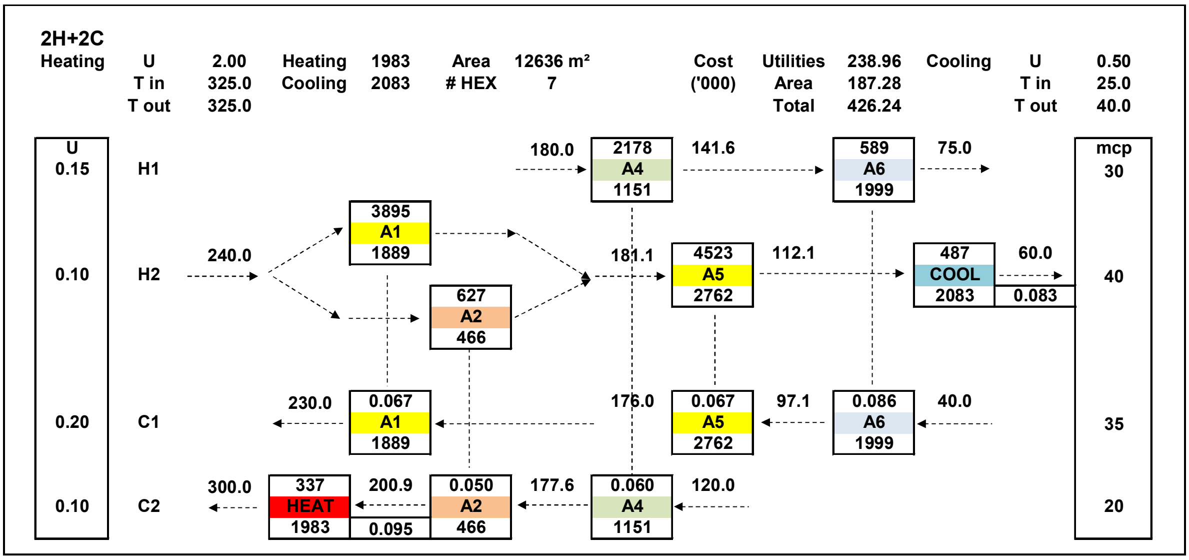

Figure 12.7

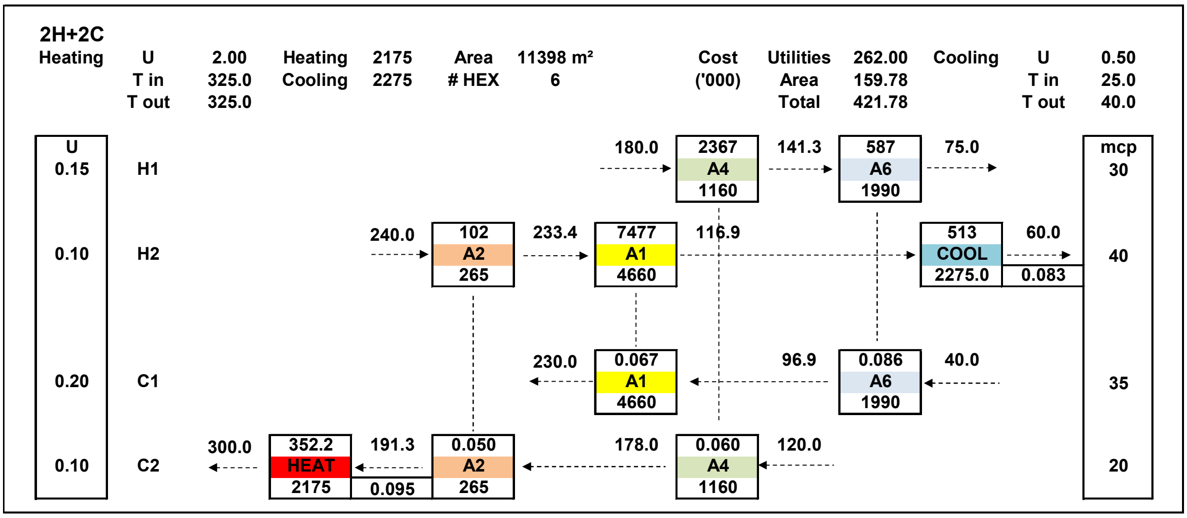
2H+2C
Heating
U
T in
T out
2.00
325.0
325.0
Heating
Cooling
2175
2275
Area
HEX
11398 m²
6
Cost
('000)
Utilities
Area
Total
262.00
159.78
421.78
Cooling
U
T in
T out
0.50
25.0
40.0
U
0.15
0.10
0.20
0.10
H1
H2
C1
C2
mcp
30
40
35
20
180.0
2367
A4
1160
141.3
587
A6
1990
75.0
240.0
102
A2
265
233.4
7477
A1
4660
116.9
513
COOL
2275.0
60.0
0.083
230.0
0.067
A1
4660
96.9
0.086
A6
1990
40.0
300.0
352.2
HEAT
2175
191.3
0.095
0.050
A2
265
178.0
0.060
A4
1160
120.0

Figure 12.8