PINCHCO

Pinch Analysis with crisscross optimization prior to design

Case 20 - Synthesis of Heat Exchanger Networks - A Comparison of Methods

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There are two tendencies in heat exchanger network design: the Pinch Technology method with sequential targeting and design steps and the more computer oriented procedures, based on mathematical programming techniques that should solve the problem in one single step. More recent developments try to combine the advantages of both techniques.

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 [4] Case 2 on the Pinchco website).

Part I

A further development of the Pinch Technology based Supertarget procedure has led to a combination of the Area Targeting Model (ATM) using shifting procedures mentioned before and Hypertargets (ref. [1], [2] and [3], Hypertargets: a Conceptual Programming approach for the optimisation of industrial heat exchanger networks ï Parts I, II and III, V. Briones, A.C. Kokossis).

In this Part I the results of the ATM and Hypertargets are compared with the results obtained by analysis with Crisscross Optimisation, combined with LP and/or heuristic rules.

Problem 1.

The data set of example 1 in [1] is shown in Table 20.1. Utility data have been added in order to enable a trade-off analysis which, however, will confirm that lowest cost is obtained with zero utility loads. Also shift values for the ATM reported in [1] and those obtained by crisscross optimisation have been added.

Table 20.1

Tsupply	Ttarget	Heat	Shift ATM	Shift Crisscross	U*f	Description	mcp
°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

Heating 200°C, 130/kW Cooling 10-15°C, 30/kW

HEX Cost = 8600 + 670 $^{0.83}$ Life time: 10 years Discount rate: 15%

Trade-off data are shown in Figure 20.1 and Figure 20.2. The cost figure confirms that the case with no utilities has the lowest cost. Minimum cost target in the classic approach is 543 K for 5 units with an area of 2079 m²; in the crisscross case the cost target is 502 K with an area of 1875 m².

Figure 20.1

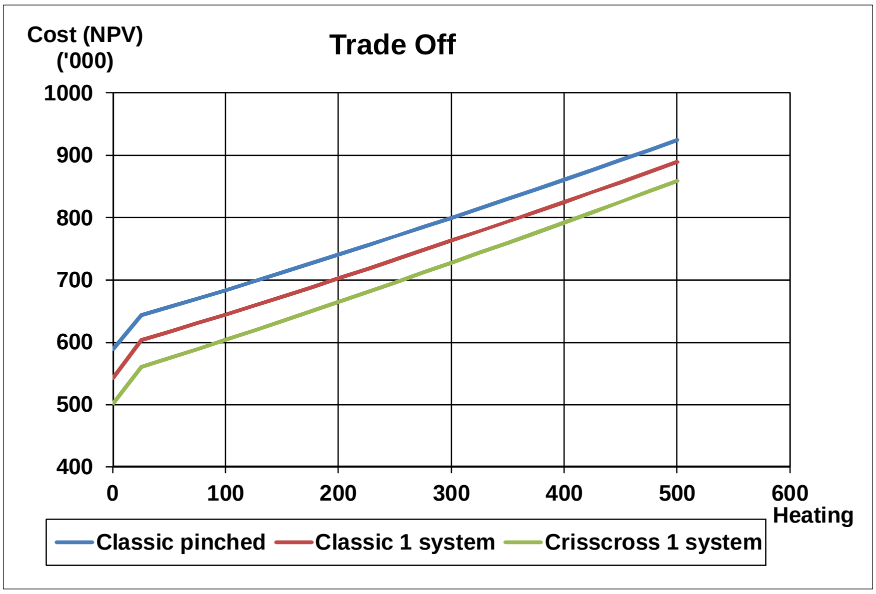
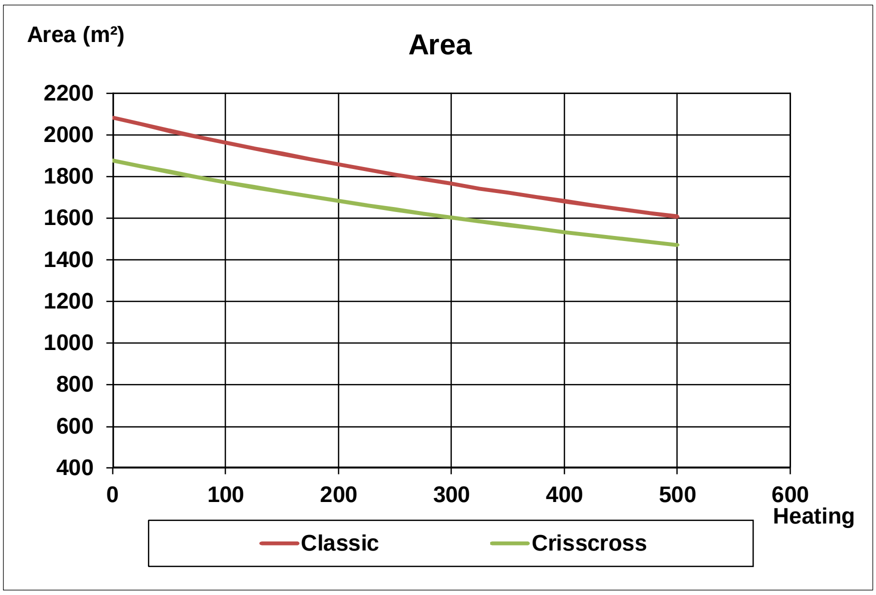


Figure 20.2



The best solution suggested by the ATM as reported in [1] is shown in Figure 20.3. A network with 6 units developed after crisscross optimisation is shown in Figure 20.4; a network with 5 units is shown in Figure 20.5. Solutions obtained by crisscross optimisation require a 40% lower area, have a 25% lower cost and score significantly better than those obtained on the basis of the ATM. Reportedly, the conventional transhipment model would come up with one of the solutions mentioned in [1] and, consequently, would not generate the best solution either.

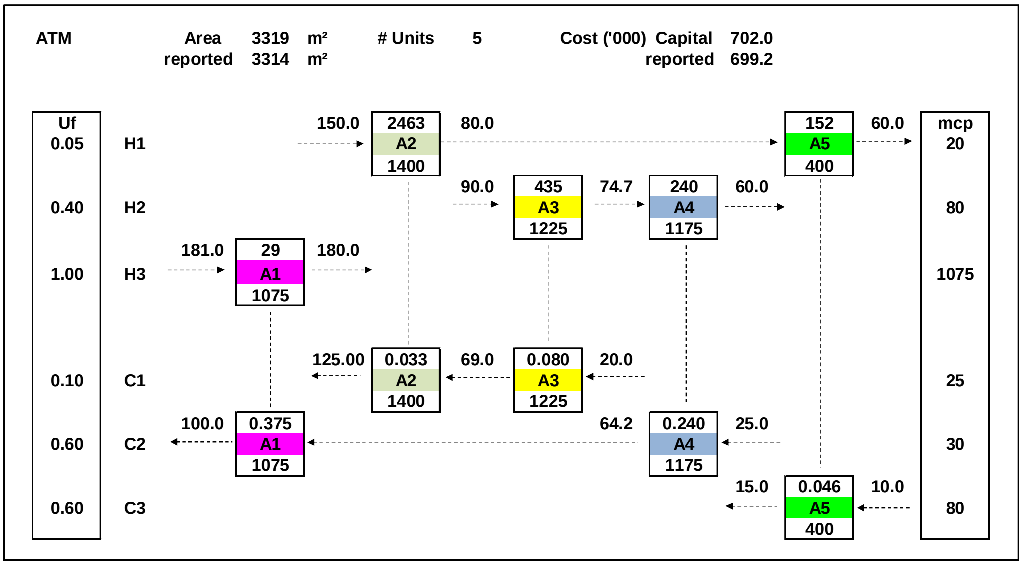


Figure 20.3

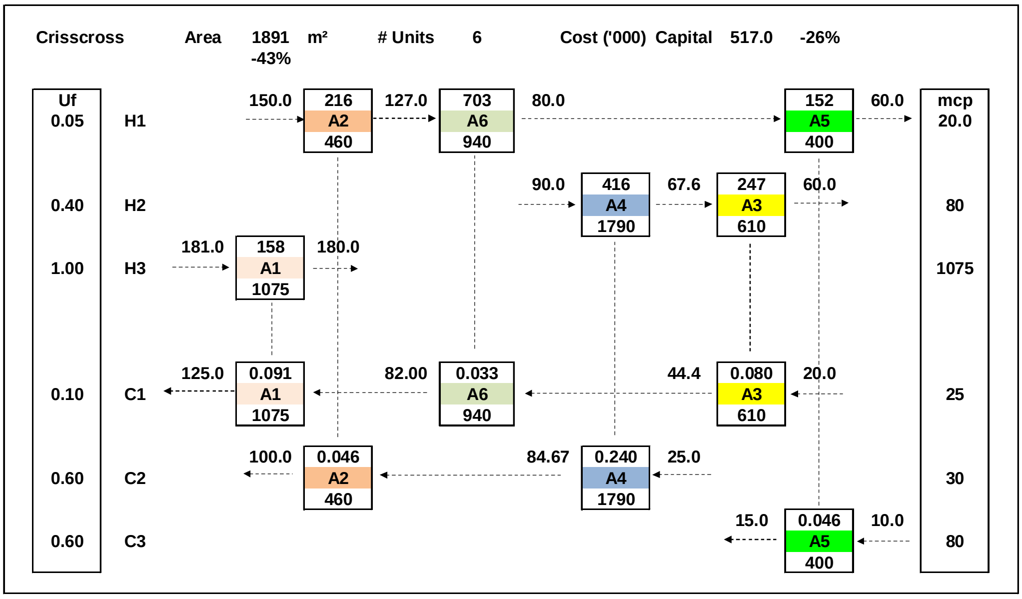


Figure 20.4

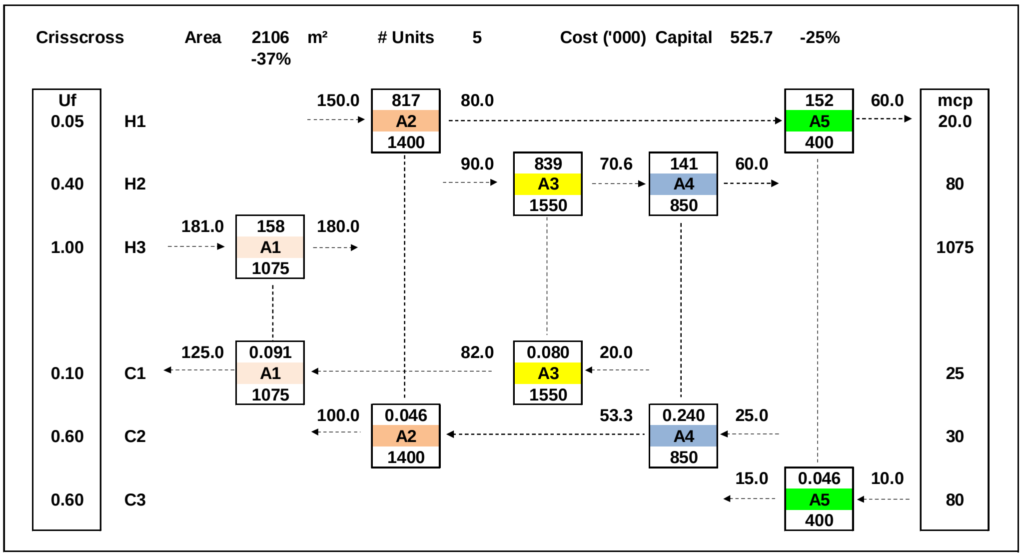


Figure 20.5

A network developed from the grid in classic pinch analysis is shown in Figure 20.6. The area is 2.9% higher than for the network with crisscross; the cost, however, is 2.5% lower. The reason for this unexpected result is the fact that the heat exchanger cost function promotes unequal surface areas. As can be seen from Table 20.2, the inequality of the surface areas in the classic case is much bigger than in the crisscross solution.

Figure 20.6

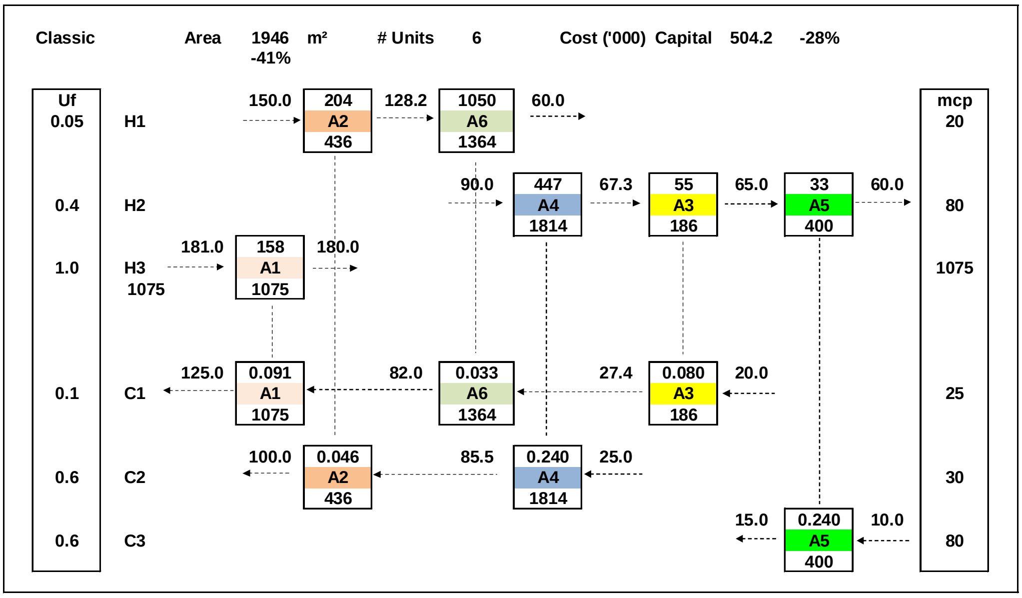


Table 20.2

	Cost	Area	Average	Standard deviation
	'000	m²	m²	m²
Crisscross 6 units	517	1891	315	194
Classic 6 units	504	1946	324	351

Problem 2.

The data set of example 2 case 1 in [1] with equal heat transfer coefficients can be solved directly by vertical heat exchange in the grid. Case 2 in [1] with unequal heat transfer coefficients has been extensively discussed in [4]. The crisscross analysis generates grid diagrams that enable direct synthesis of the networks for minimum area as well as for minimum cost by vertical heat exchange in the grid diagrams without any further sophisticated programming.

Problem 3.

The data set of example 3 in [1] is shown in Table 20.3. Shift values have been optimised for the given heating of 100 MW; this load was chosen on the basis of the trade-off curves in Figure 20.7 and would seem to be a good starting point for design.

Table 20.3

Tsupply °C	Ttarget °C	Heat kW	DT-shift K	U kW/K,m²	Descript. -	mcp kW/K
140	40	47000	-2	16.00	H1	470.0
160	120	33000	-3	2.00	H2	825.0
210	45	7000	0	0.90	H3	42.4
260	60	20000	-2	0.80	H4	100.0
280	210	25000	0	0.40	H5	357.1
350	170	9000	30	0.10	H6	50.0
380	160	30000	35	0.08	H7	136.4
270	385	95000	-1	0.80	C1	826.1
130	270	70000	1	0.44	C2	500.0
20	130	40000	35	0.08	C3	363.6
450	310	100000	29	0.10	Heating	
20	25	66000	0	2.30	Cooling	

Area Cost = 20000 + 1200 area $^{0.83}$

Hot utility cost = 40/kW,year Cold utility cost = 4/kW,year

Life time: 5 years Discount rate 15%

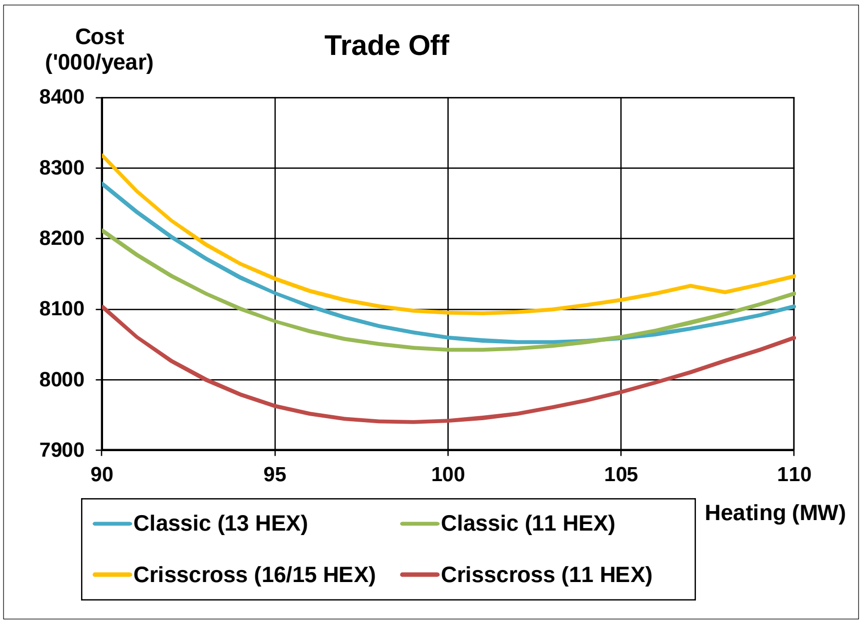


Figure 20.7

The study of example 3 in [1] assumed perfect counter-current heat exchange. The fact that the final network shall be designed with standard Shell & Tube 1-2 exchangers was anticipated here and a Ft factor of 0.9 was assumed for the analysis.

Example 3 [1] was revisited in example 5 [1] with the use of Hypertargets. The trade-off curves in [1], however, seem to be incomplete and the example has been revisited again in [3] as example 1. At the same time, the use of Shell & Tube 1-2 exchangers was taken into account. In Figure 1 of [3], the Supertargetsô trade-off curve shows a step-change at a DTMin of 37 K and would suggest optimum solutions at that point. This step-change, however, is ñhome-madeò in the analysis itself by the assumption of segregation of the network at the pinch which, for a DTMin of 37 K and lower, is caused by hot stream H2; for higher DTMin values, the pinch stream in classic pinch analysis is H5 instead of H2.

The shifted Composite Curves are shown for the classic and for the crisscross analysis in Figure 20.8 and Figure 20.9 respectively. Classic CC’s show a pinch caused by hot stream H5 and a narrow zone down to a near pinch at 150°C caused by H2, suggesting small driving forces in the network in that area. CC’s of crisscross optimisation show a pinch by H2 at 150°C and a pinched zone above 280°C. The expectation about where the network will show lowest driving forces is different.

The minimum number of units is 11. Segregation at the pinch, caused by stream H5 (Classic approach) would require 13 units; segregation at the beginning of H2 (Crisscross) would require 16 units; this has a serious impact on the results of the trade-off (Figure 20.7) and this illustrates that segregation in two systems should be done with care and not necessarily automatically.

Figure 20.8

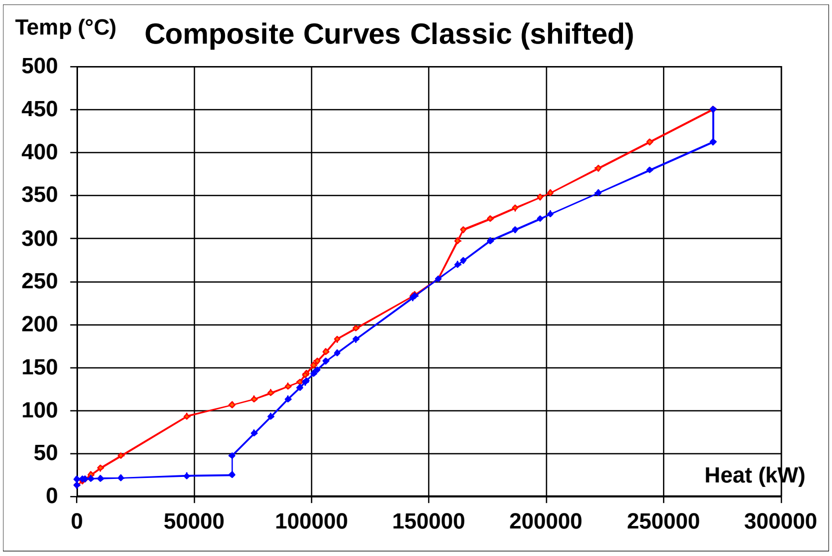
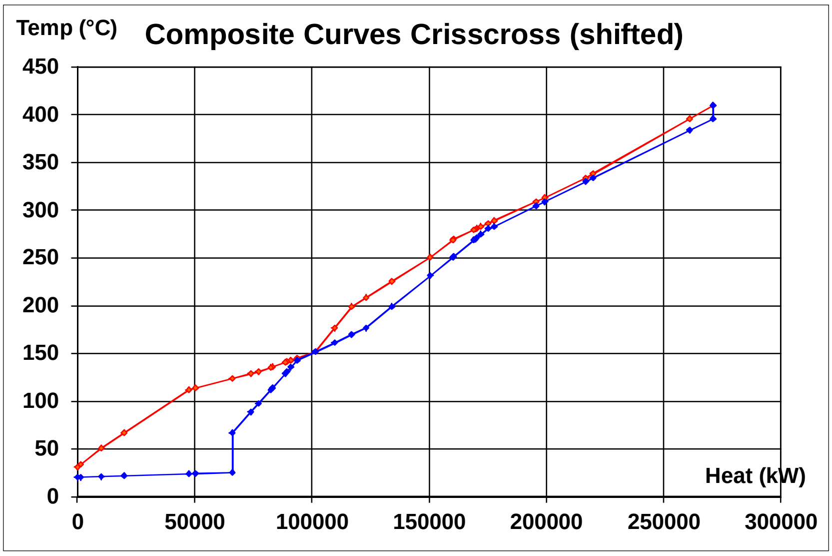


Figure 20.9



In the present study, the following steps were applied within a heuristic approach with the objective to synthesize a network without splits:

- Classic pinch analysis and analysis with crisscross optimisation
- Trade-off in order to define an appropriate heating load (set at 100 MW)
- Generation of the corresponding grid diagram resulting into 19 integration bands
- Reduction of the number of integration bands from 19 to 9 whilst maintaining the character of the problem
- Synthesis of the network for 9 integration bands with Linear Programming resulting into 34 units
- Optimisation and simplification by incremental evolution whilst unwinding remaining splits

In parallel, a smart tick-off procedure was used for direct synthesis of a network without splits, followed by incremental evolution.

A large number of networks could be developed within a narrow cost range.

The best network as reported in [3] Figure 1 Design C is reproduced in Figure 20.10. The best network developed in this study is shown in Figure 20.11 for heating limited to 100 MW and in Figure 20.12 without such limitation

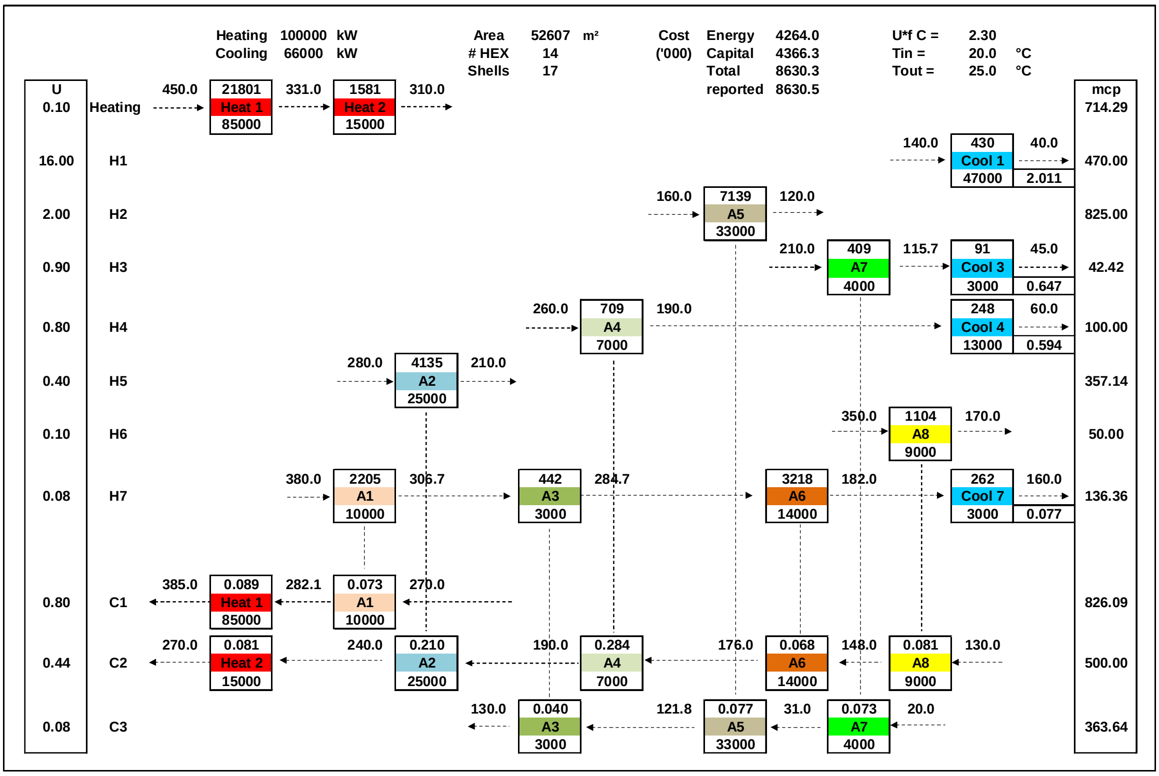


Figure 20.10.

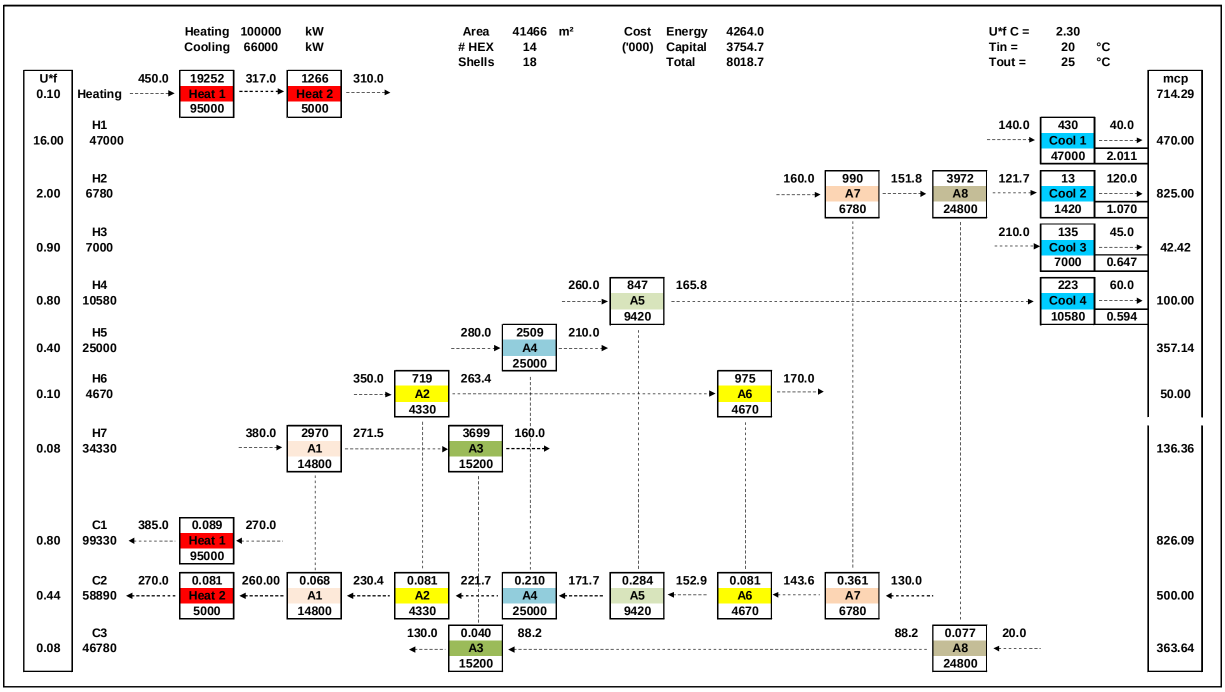


Figure 20.11

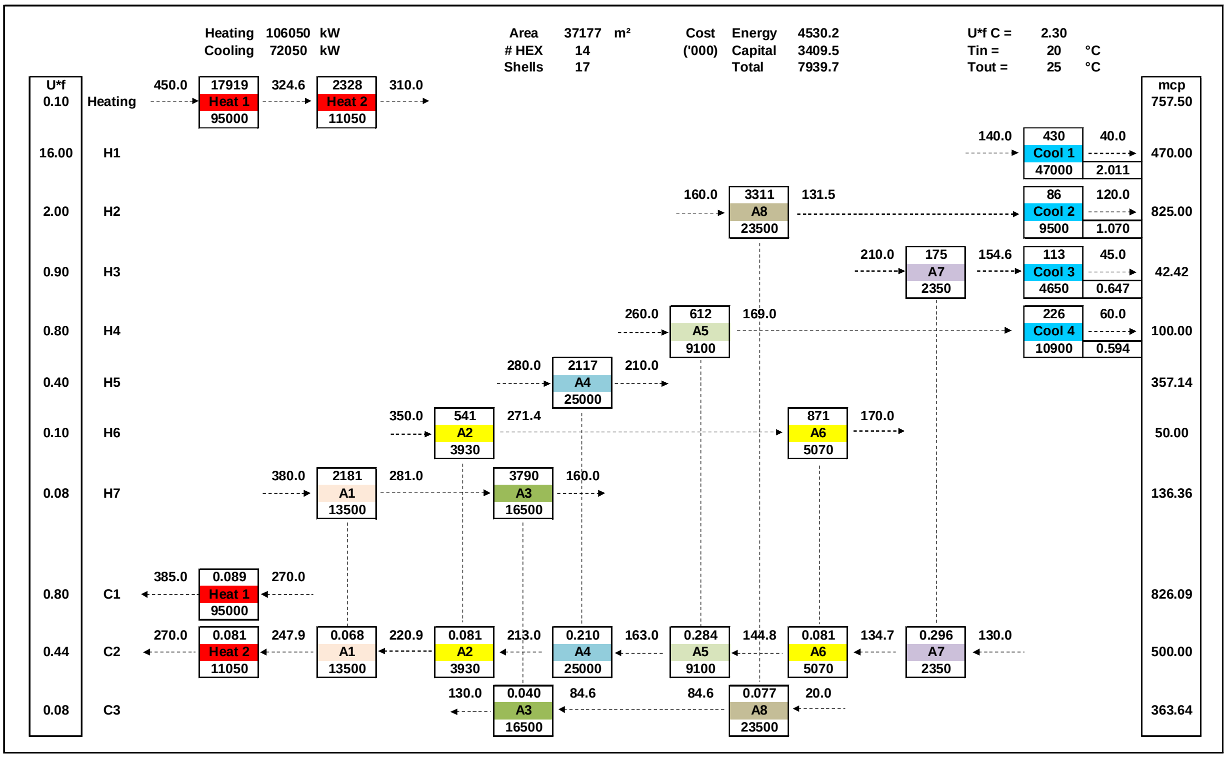


Figure 20.12

The results can be compared in Table 20.4. The method with crisscross optimisation and heuristics scores significantly better than the ATM method with Hypertargets.

Table 20.4

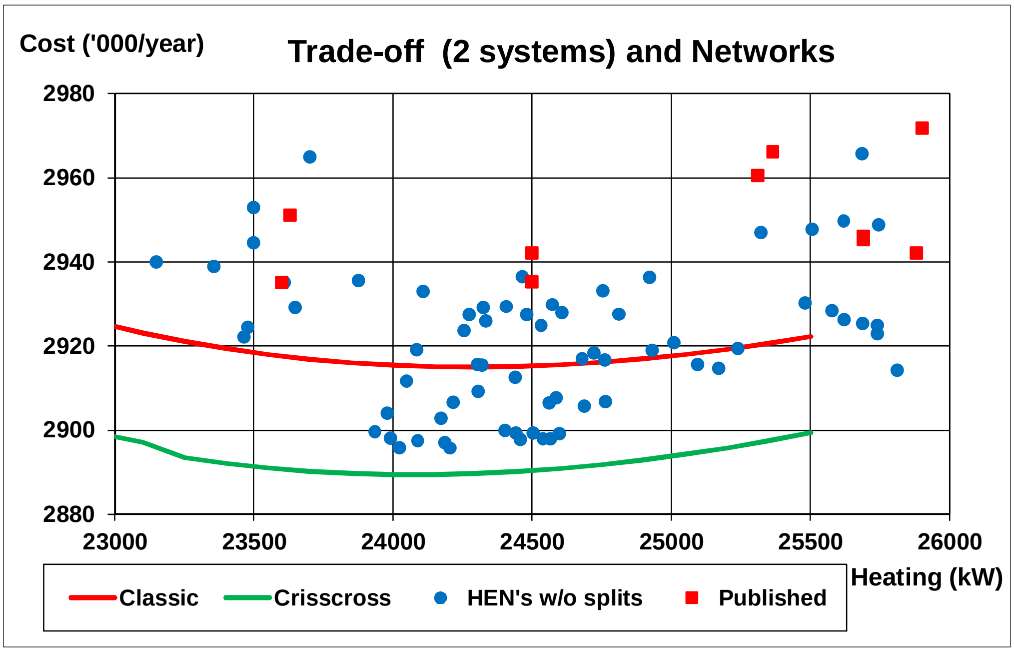
	Heating kW	Area m²	# HEX -	# Shells -	Cost ('000/y) Energy	Capital	Total
Best Reference [3]	100000	52607	14	17	4264.0	4366.3	8630.3
Crisscross optimisation	100000	41466	14	18	4264.0	3754.7	8018.7
+ heuristics	106050	37177	14	17	4530.2	3409.5	7939.7

Problem 4.

Problem 4 is the 9SP Aromatics Plant data set, treated in [1] as example 7. This example has been studied by many other authors in the past and has also been studied extensively by this author. Results are available on the Pinchco website ([5] and [6]) and the networks without split are summarised in Figure 20.13.

The results of the ATM combined with Hypertargets are not included in this summary; with a lowest cost network of 2 971 000/year, the proposed networks would be uncompetitive.

Figure 20.13



Part II

Development of Mathematical Programming (MP) techniques include using of MILP as well as MINLP. In some cases, this might require approximation of LMTD calculations and linearization of cost functions. Whilst the Pinch Analysis (PA) based procedures are sequential (first targeting, then design), the MP procedures aim at solving the problem in a single step.

Problem 5.

A comparison is made between PA oriented and MP based procedures using the example of a retrofit of a Crude unit pre-heating train [7]. The document in reference [7] is a comparison between the classic Pinch Analysis procedure and the MP-based MILP Heat Integration Transportation Model.(HIT).

The specific heat value of the crude which is temperature dependent was reconstructed after sectionalising the hot streams and the crude on the basis of the existing network and the additional information in [7]. The mcp of the Crude is further approximated with second order polynomials in 3 sections with a first section below the desalter, a second section between desalter and original inlet temperature of the furnace and a third section between that temperature and the Crude target temperature; this should improve the results of the analysis as well as the design.

Since stream specific U values are not reported in [7], a constant value of 0.7 kW/K,m² was taken over the whole temperature range of the Crude and corresponding specific U values of the hot streams were derived from the surface areas of the existing heat exchangers; it was assumed that this would not have a significant effect on the comparison. In [7], no information could be found related to U values for stream sections cooled down in coolers. These values were estimated with best endeavour.

The resulting data set is shown in Table 20.6.

Financial conditions are summarised in Table 20.5. The objective of the retrofit was to maximise the NPV. For the calculation of the NPV, the impact of changes in coolers and cooling loads was disregarded as was done in [7]. The financial data were also used to estimate the optimum heating load for the retrofit; since in reality this would be influenced by cooling water cost, a pro forma water cost of 5 /kW,year was used to check the impact. The optimum heating load was 26300 kW without cooling water cost and 26150 kW with this cost. A value of 26200 kW was retained (see also Figure 20.16).

Table 20.5

Shell fix cost	127129		
Area addition cost per m²	271.20		
Lang factor	1.5		
Project Lifetime for NPV	10 years	Retrofit Pay-back target	2.5 years
Discount rate	10.0%	Discount rate	10.0%
		Retrofit Annuity factor	47.2%
Furnace fuel cost	100 /kW,year		
Furnace efficiency	80%		
Cooling water cost (pm)	5 /kW,year		

Table 20.6

Tsupply °C	Ttarget °C	Heat kW	DT-shift K	U kW/K,m²	Descript. -	mcp avg
360.0	290.0	4640	-4	0.577	VR1	66.3
290.0	115.0	4940	-4	0.500	VR2	28.2
303.6	270.2	7800	-2	0.470	LCR	233.5
359.6	280.0	1930	-3	0.500	SRQ	24.2
250.6	212.6	5470	2	0.284	HVGO1	143.9
212.6	167.6	6070	2	0.291	HVGO2	134.9
167.6	90.0	9480	8	0.291	HVGO3	122.2
249.8	190.0	1990	-7	0.933	LGO1	33.3
190.0	125.4	2000	-10	0.899	LGO2	31.0
125.4	110.0	450	-14	0.899	LGO3	29.2
277.0	206.0	1880	-6	0.682	HGO1	26.5
206.0	121.9	2000	-7	0.698	HGO2	23.8
210.0	181.9	3360	2	0.373	MCR1	119.6
181.9	163.0	2180	4	0.373	MCR2	115.3
170.1	101.5	2400	-6	0.542	KERO1	35.0
101.5	60.0	1320	-7	0.542	KERO2	31.8
140.2	69.3	7530	8	0.289	TCR1	106.2
69.3	40.0	2880	5	0.289	TCR2	98.3
178.6	108.9	3300	-5	0.600	LVGO	47.3
117.7	50.0	8310	-6	0.600	OVHD	122.7
30.0	70.0	7530	0	0.700	Crude 1a	188.3
70.0	80.0	2000	0	0.700	Crude 1b	200.0
80.0	91.9	2400	0	0.700	Crude 1c	201.7
91.9	101.6	2000	0	0.700	Crude 1d	206.2
101.6	130.0	6070	0	0.700	Crude 1e	213.7
130.0	145.0	3360.0	0	0.700	Crude 2a	224.0
145.0	153.7	1990	0	0.700	Crude 2b	228.7
153.7	161.9	1880	0	0.700	Crude 2c	229.3
161.9	185.0	5470	0	0.700	Crude 2d	236.8
185.0	216.7	7800	0	0.700	Crude 2e	246.1
216.7	234.8	4640	0	0.700	Crude 2f	256.4
234.8	283.6	13130	0	0.700	Crude 3a	269.1
283.6	350.0	25960	0	0.700	Crude 3b	391.0
800.0	350.0	26200	37	0.100	Heating	
10.0	20.0	21900	0	1.000	Cooling	

The existing network is reproduced in Figure 20.14.

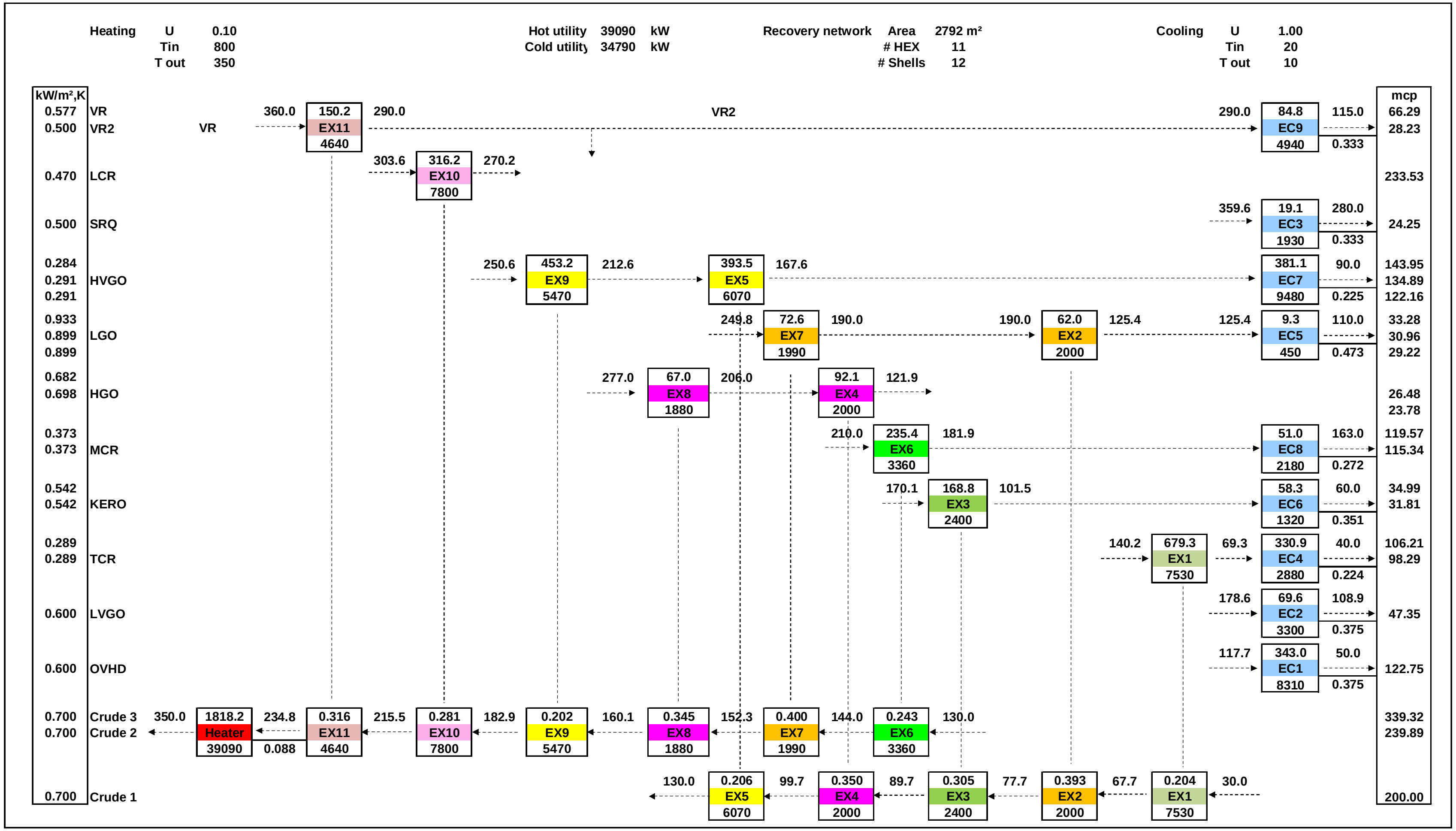


Figure 20.14

A provisional Ft correction factor of 0.9 was used for the analysis; this was considered by multiplying the individual U values of Table 20.6 by the factor 0.9. In the design stage later, a correct Ft factor for Shell & Tube 1-2 exchangers was calculated and applied for each individual heat exchanger; for said Ft factor, a minimum value of 0.7 was imposed. Area size was limited to a maximum of 500 m² per shell and, as in [7], also an EMAT (Exchanger Minimum Approach Temperature) of 5K was considered.

The detailed fragmentation of the process streams as shown in Table 20.6 is useful to take into account the temperature dependency of these streams; it is not necessarily practical, however, for starting a detailed design because of the too high number of segments and for that reason the segments were regrouped above and below the pinch respectively in a ñreducedò data set. It is obvious that for doing so, the location of the pinch must first be known, but that can easily be identified by a simple iteration. The result is shown in Table 20.7.

Table 20.7

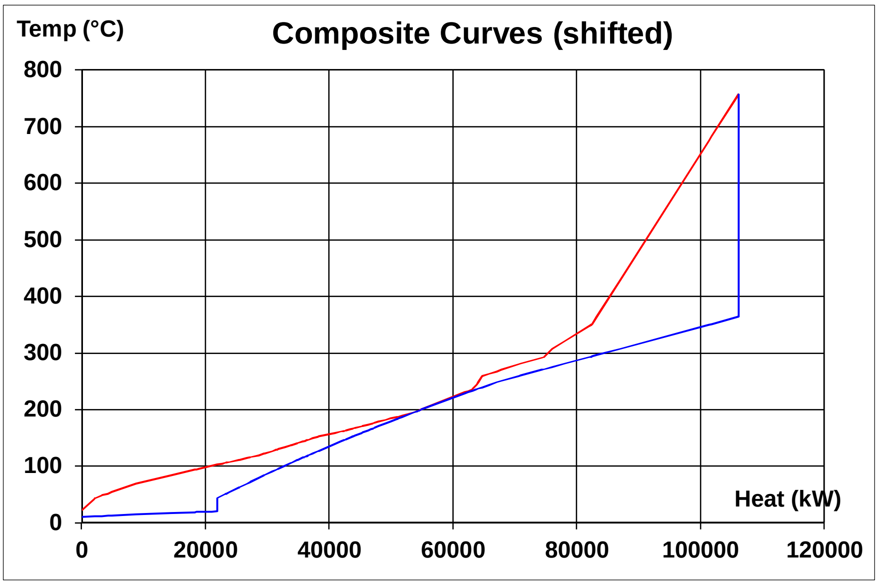
Hot streams linearised to 14 + Heating						
pinch stream = N°10	Units:	24				
Tsupply °C	Ttarget °C	Heat kW	DT-shift K	U kW/K,m²	Descript. -	mcp avg
360.0	290.0	4640	2	0.577	VR	66.3
290.0	115.0	4940	-4	0.500	VR2	28.2
303.6	270.2	7800	-3	0.470	LCR	233.5
359.6	280.0	1930	3	0.500	SRQ	24.2
250.6	212.6	5470	3	0.284	HVGO1	143.9
212.6	90.0	15550	2	0.291	HVGO2+3	126.8
249.8	110.0	4440	-6	0.933	LGO1+2+3	31.8
277.0	206.0	1880	-5	0.682	HGO1	26.5
206.0	121.9	2000	-7	0.698	HGO2	23.8
210.0	163.0	5540	1	0.373	MCR1+2	117.9
170.1	60.0	3720	-6	0.542	KERO1	33.8
140.2	40.0	10410	8	0.289	TCR1	103.9
178.6	108.9	3300	-6	0.600	LVGO	47.3
117.7	50.0	8310	-9	0.600	OVHD	122.7
30.0	130.0	20000	0	0.630	Crude 1	200.0
130.0	185.0	12700	0	0.630	Crude 2a	230.9
185.0	234.8	12440	0	0.630	Crude 2b	249.8
234.8	283.6	13130	0	0.630	Crude 3a	269.1
283.6	350.0	25960	0	0.630	Crude 3b	391.0
800.0	350.0	26200	37	0.100	Heating	
10.0	20.0	21900	0	1.000	Cooling	

The analysis of the reduced data set indicates that the minimum number of heat exchanger units would be 13 above and 11 below the pinch.

The (shifted) composite curves are shown in Figure 20.15. A tight area starts with a near to second pinch caused by stream HVGO at 251 °C, through the pinch at 210 °C caused by stream MCR. The narrow zone covers 11300 kW or roughly 10% of the total integration.

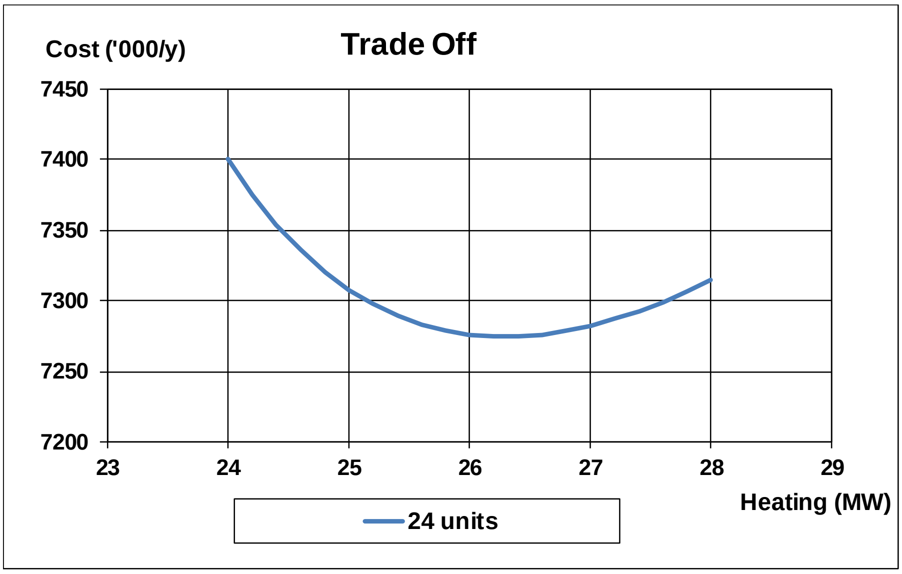
For retrofit studies, classic pinch analysis makes use of the area efficiency concept in order to define the optimum DTMin or the optimum heating load. There is, however, neither a technical nor a financial justification for such approach. The objective of a retrofit is not only to keep the existing area efficiency, but also to improve it. The approach adopted here was to set a pay-back target (2.5 years in this case) and to define the annual fix cost in combination thereof together with the discount rate; this led to the Retrofit Annuity factor of 47.2% mentioned in Table 20.5.

Figure 20.15.



Trade-off including cost of cooling water leads to the curve in Figure 20.16. With the investment cost formula of Table 20.5, the number of units is not influencing the optimum heating load for obtaining minimum cost. A heating load of 26200 kW was retained as target.

Figure 20.16



A first LP run on the data set of the grid produced by the analysis (either on the full data set or the ñreducedò one) indicates that complicated stream splits would be required. However, it looks appropriate to have the heater in one single piece at the end of the Crude and, consequently, the heating load shall be moved up in the grid. For a retrofit, it is also advantageous to reuse existing matches and, so, the position of existing exchangers EX11, EX10 and EX9 is checked by adjusting the grid as shown in Table 20.7.

Table 20.7

Shifting of heat loads in the grid for network simplification *)
Above the desalter
put Heater at the hot end of the Crude
use heat of VR before Heater
use heat of SRQ before heat of VR
use heat of LCR before heat of SRQ
move heat of KERO to below desalter
move heat of LVGO to below desalter
Below the desalter
align all coolers in the last band
move heat of MCR to above desalter
do not recover heat of OVHD
do not recover heat of VR2 below desalter
recover all heat from LGO
recover all heat from LVGO
use heat of LGO after heat of KERO and TCR
use heat of LVGO after heat of LGO
use heat of HGO after heat of LVGO
synthesise HEN with LP
align resulting heat loads below desalter in 2 branches
*) sequence is defined on the Crude stream from cold to hot

The results indicate that it is appropriate to study initial designs with matches in a sequence Heater ï VR1 ï SRQ ï LCR on the hot side of the Crude, which would keep existing exchangers EX11 and EX10 in front of the splits. It also looks interesting to use the KERO heat entirely below the desalter and the MCR heat entirely above the desalter. Also the heat of LVGO shall be used entirely below the desalter.

Pinch design would suggest stream splitting at the pinch; instead of that, stream splitting will be applied directly after the desalter to cover the narrow zone aside the pinch.

Above the desalter, the remaining heat loads to recover are from VR2, HVGO, HGO, MCR and LGO. The stream VR2 is covering the complete remaining temperature span of the Crude and gets allocated one branch of the split. HVGO and MCR have high and comparable mcpôs and get allocated a second branch of the split; between them, MCR has the lowest mcp and the lowest target temperature which is also hard; therefore, MCR is put first in the branch and HVGO is put last. HGO and LGO both have small mcpôs; a third branch of the split is allocated to them; both have soft target temperatures in the branch but LGO has the lowest target temperature and is put first in the branch. Herewith, the concept for an initial design above the desalter is ready.

As also summarised in Table 20.7, the grid below the desalter can be simplified by pulling all coolers together in one single cooling band. Although the heat of OVHD would be recovered in a new design, that heat is not used in the existing design and it is not absolutely required for a retrofit either; therefore, that heat can be rejected. Also the heat from VR2 below the desalter can be rejected. On the other hand, all heat from LGO and LVGO can be recovered and the target temperatures of LGO, LVGO and HGO can be moved further up in the grid.

The conceptual network below the desalter produced by LP is shown in Figure 20.17; this can be reorganised into 2 branches as shown in Figure 20.18 and will serve as initial design below the pinch.

Alternatively, the network below the pinch can be designed by analysis of the characteristics of the heat loads. There are 6 heat loads left to recover below the desalter. The HVGO and TCR have large mcp's and a first branch of the Crude can be allocated to them. HVGO has the highest inlet temperature and the highest mcp and is put on the high temperature end of the branch. The 4 other heat loads are put on a second branch. HGO has the highest hard target temperature and the lowest mcp and is therefore put at the high temperature end. Then, KERO has the lowest hard supply temperature and the lowest mcp and is put at the cold side. LGO has a lower temperature level and a lower mcp than LVGO and is put after KERO; LVGO is then between LGO and HGO. The sequence KERO, LGO, LVGO, HGO confirms the result obtained before by LP.

The initial design concepts were put into a simulation flowsheet for final optimisation by incremental evolution.

The HIT network proposed in [7] is reproduced in Figure 20.19; with an area of 6572 m², the deviation from the area reported in [7] is only -0.83% which should be acceptable. The best network of this study is shown in Figure 20.20.. The heating load of the retrofit network (26114 kW) is on target, pay-back is 2.53 years and also very close to the target of 2.5 years; the NPV is 3.89 % higher than that for the network reported in [7]. The results can be compared in Table 20.8

This example case shows that it is possible to set realistic targets, which are also achievable. Pinch analysis combined with smart design heuristics scores better than the one-step HIT procedure.

Table 20.8

	Heating	Additional area	Total # Shells without utilities	NPV	Simple Pay-back
	kW	m²	-	'000	years
HIT Network in [7]	25960	4467	26	6005.9	2.73
This study	26114	4453	24	6239.4	2.53
Delta				+3.89%	

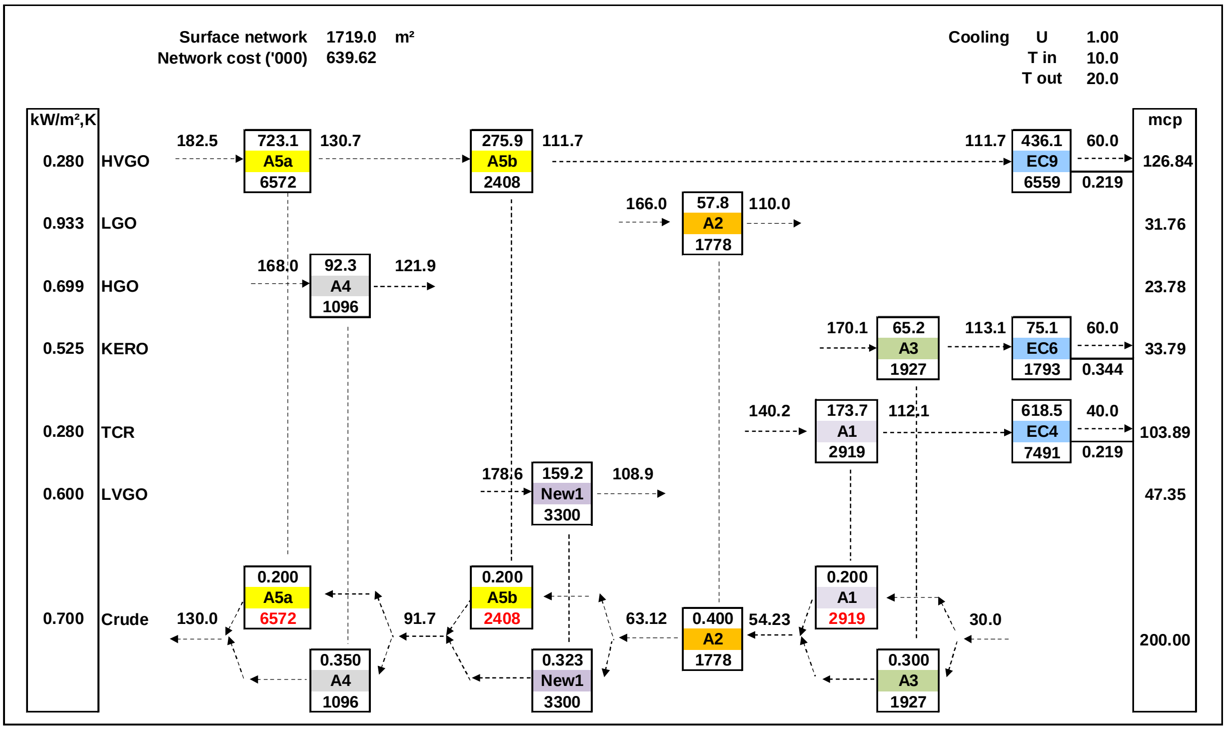


Figure 20.17

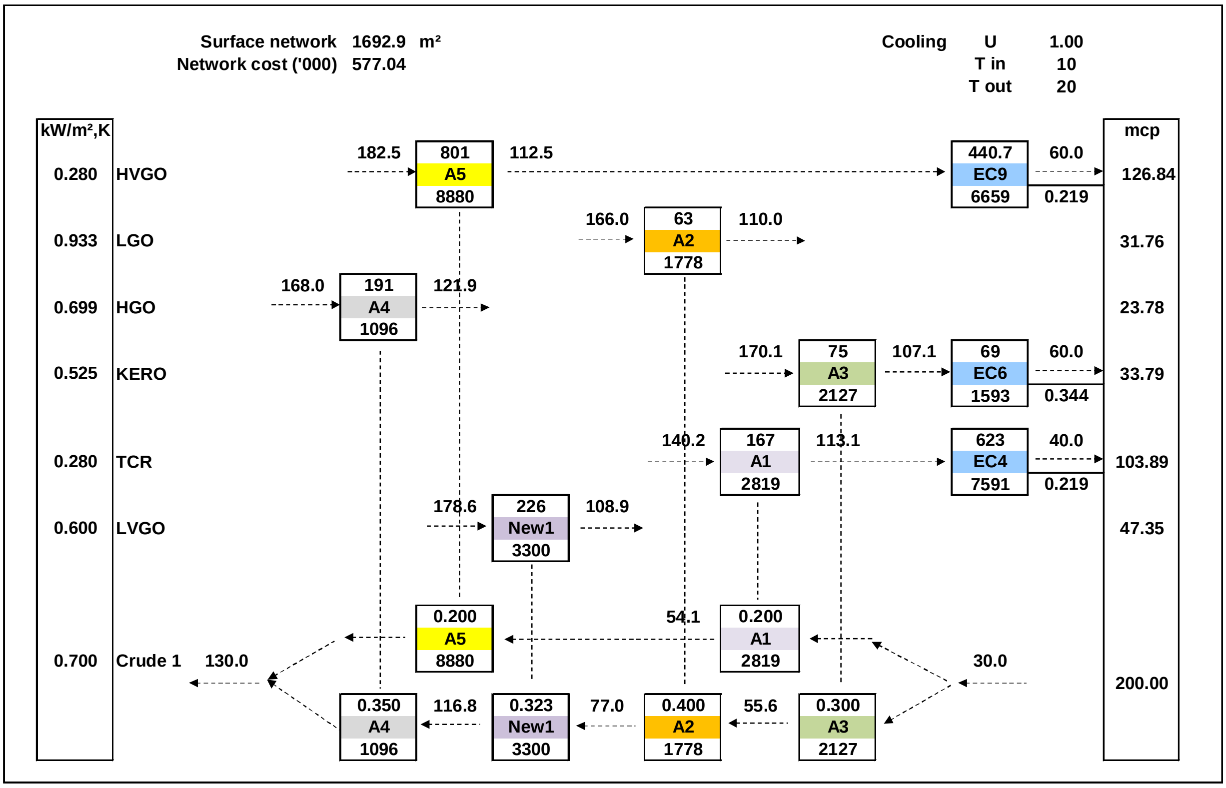


Figure 20.18

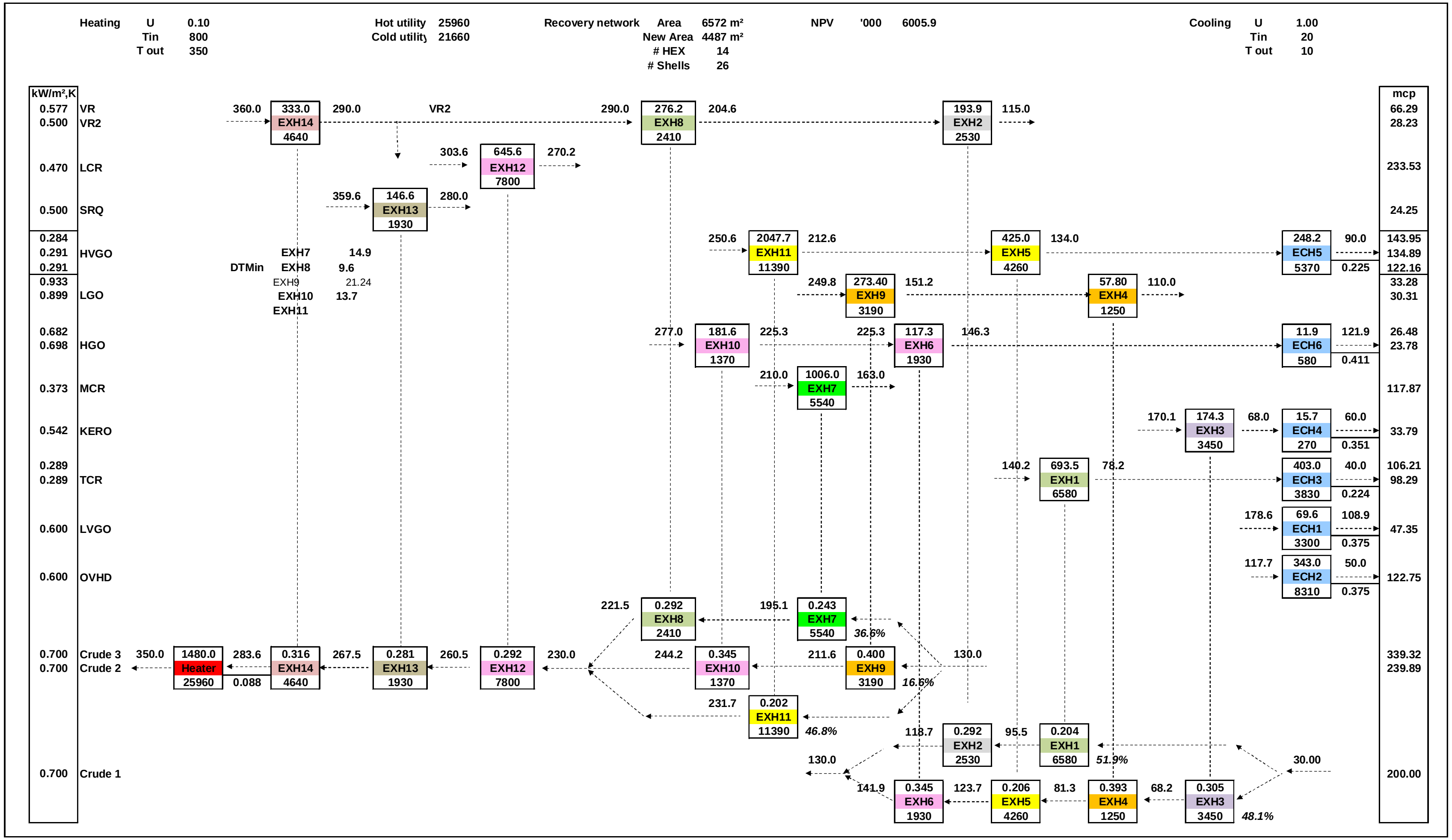

Heating U 0.10
Tin 800
T out 350
Hot utility 25960
Cold utility 21660
Recovery network Area 6572 m²
New Area 4487 m²
HEX 14
Shells 26
NPV '000 6005.9
Cooling U 1.00
Tin 20
T out 10
kW/m²,K
mcp
VR
VR2
LCR
SRQ
HVGO
LGO
HGO
MCR
KERO
TCR
LVGO
OVHD
Crude 3
Crude 2
Crude 1
DTMin
EXH7 14.9
EXH8 9.6
EXH9 21.24
EXH10 13.7
EXH11
Heater
36.6%
16.6%
46.8%
51.9%
48.1%

Figure 20.19

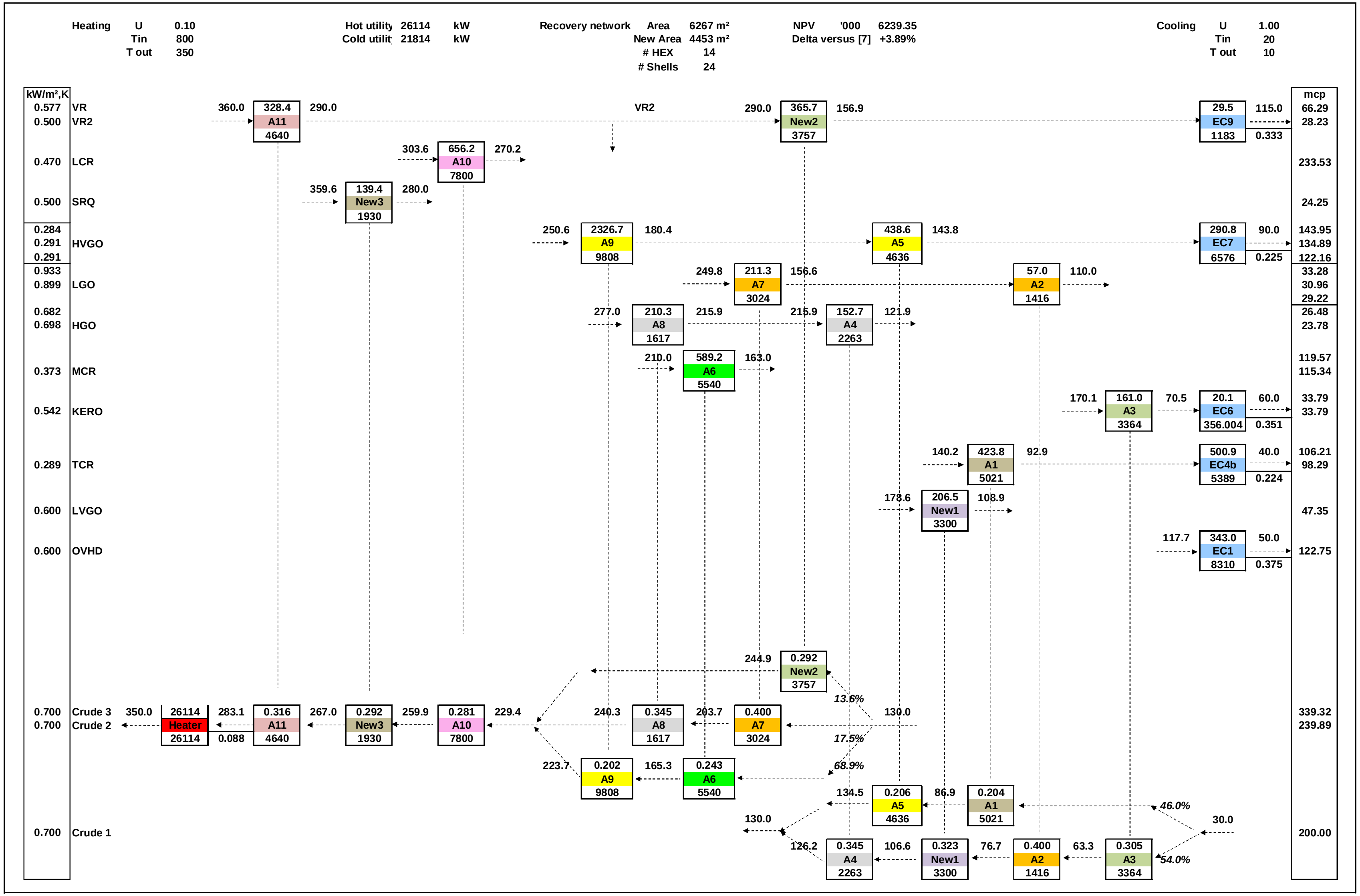

Heating U 0.10
Tin 800
T out 350
Hot utility 26114 kW
Cold utility 21814 kW
Recovery network Area 6267 m²
New Area 4453 m²
HEX 14
Shells 24
NPV '000 6239.35
Delta versus [7] +3.89%
Cooling U 1.00
Tin 20
T out 10
kW/m²,K
mcp
VR
VR2
LCR
SRQ
HVGO
LGO
HGO
MCR
KERO
TCR
LVGO
OVHD
Crude 3
Crude 2
Crude 1
Heater
A11
A10
New3
New2
A9
A5
A7
A2
A8
A4
A6
A3
A1
New1
EC9
EC7
EC6
EC4b
EC1
13.6%
17.5%
68.9%
46.0%
54.0%

Figure 20.20

References

[1] Hypertargets: a Conceptual Programming approach for the optimisation of industrial heat exchanger networks ï I. Grassroots design and network complexity. V. Briones, A.C. Kokossis, Chemical Engineering Science 54 (1999) 519-539.

[2] Hypertargets: a Conceptual Programming approach for the optimisation of industrial heat exchanger networks ï II. Retrofit design. V. Briones, A.C. Kokossis, Chemical Engineering Science 54 (1999) 541-561.

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[4] Case 2 ï Example from Gundersen and Grossmann ï Available on the website Pinchco.com and also available on ResearchGate

[5] Case 4 ï Example from Linnhoff and Ahmad ï The 9SP aromatics plant - Available on the website Pinchco.com and also available on ResearchGate (DOI: 10.13140/RG.2.1.2918.4166)

[6] Case 15 - A new tick-off procedure for synthesis of networks without splits ï Example Case 15 - The 9SParomatics Plant revisited - Available on the website Pinchco.com and also available on ResearchGate **(**DOI: 10.13140/RG.2.1.4301.0405)

[7] Retrofit of Crude Units Preheating Trains: Mathematical Programming versus Pinch Technology. Miguel Bagajewicz, Gary Valtinson, and DuyQuang Nguyen Thanh
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