Pinch analysis with crisscross optimisation prior to design
Heat exchanger network synthesis based on optimised input data sets

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Synthesis of heat exchanger networks is still a challenging task. Pinch technology, apart from the analysis itself, has also established several fundamental rules for design of the heat exchanger network to accomplish the energy targets. These rules, however, are not always conclusive and although the results can meet the energy targets, said results are not always optimal in terms of overall cost. A lot of effort has been put into development of methods and procedures for the design of optimal networks whilst the analysis itself has received much less attention.

The basic data set for synthesis of a heat exchanger network is provided by the grid of process streams and utilities. Usually, the initial network synthesised by one or another procedure is too complicated, has too many heat exchanger units and needs to be simplified, further optimised and fine-tuned. It is obvious, however, that the structure of the initial network is decisive for any outcome.

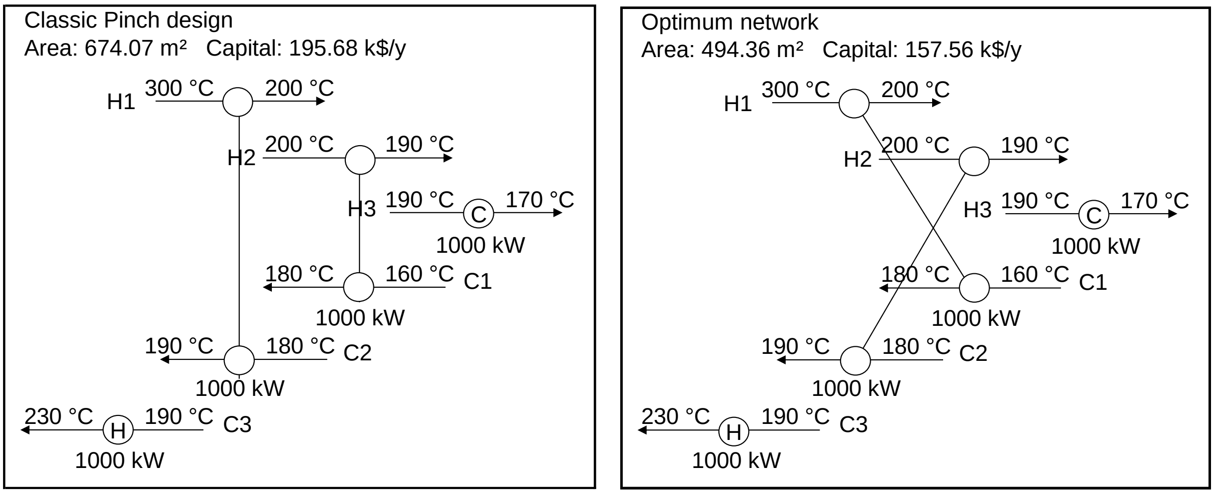
A good starting point is determined by a trade-off between energy and capital in the analysis stage. The estimation of the capital cost requires calculation of the surface area. Classic algorithms for the area targeting, based on a uniform DTmin do not produce satisfactory results in case of large differences in heat transfer coefficients (U-values). It is obvious that process streams with low U-values require a higher DT-contribution than streams with high U values. The area targeting algorithm, based on the Bath-formula, however, only works with a uniform DTMin. This weakness of classic pinch analysis has been known from the beginning in the early eighties and various efforts have been undertaken since then to develop more adequate procedures: Nishimura in 1980 [1], Suhail Ahmad in 1986 [2], R. D. Colberg and M. Morari in 1990 [3], E. Rev and Z. Fonyo in 1991 [4], X. X. Zhu in 1994 and later [5], [6], [7], M. Serna-González in 1999 [8] and later together with Arturo Jiménez and J. M. Ponce-Ortega [9] [10], V. Briones and A.C. Kokossis in 1999 [11], J. Jezowski et all. in 2003 [12]. So far, no systematic procedure has been developed that is capable of producing satisfactory results.

A new procedure is proposed for calculation of the area (and cost) target that takes into account stream specific DTMin contributions. A data set from Gundersen and Grossmann [13] will be used as *Example 1* to demonstrate the procedure. The data set is shown in Table 1. The original data set has been completed with prices for utilities and investments to illustrate differences in total cost.

Energy targets for an overall DTMin of 20 K are 1000 kW Heating and 1000 kW Cooling.
The classic pinch design is shown in Figure 1(a); the surface area is 674 m². Energy cost is 140 k$/year, capital cost is 195.68 k$/year.
The optimum design is shown in Figure 1(b); the surface area is reduced to 494 m². For the same energy cost, the capital cost is only 157.56 k$/year. Classic pinch analysis fails to produce the optimum result.

Table 1 Data set example from Gundersen and Grossmann.

Data example Gundersen and Grossmann						Optimum shift for	
		Classic pinch analysis				minimum	minimum
Tsupply	Ttarget	Heat	DTMin	U*f	Description	Area	Cost
°C	°C	kW	K	kW/K,m²	-	K	K
300	200	1000	10	0.1	H1	0	0
200	190	1000	10	1.0	H2	0	0
190	170	1000	10	1.0	H3	0	0
160	180	1000	10	0.1	C1	30	30
180	190	1000	10	1.0	C2	0	0
190	230	1000	10	1.0	C3	7	20
350	350	1000		4.0	Heating		
30	50	1000		2.0	Cooling		



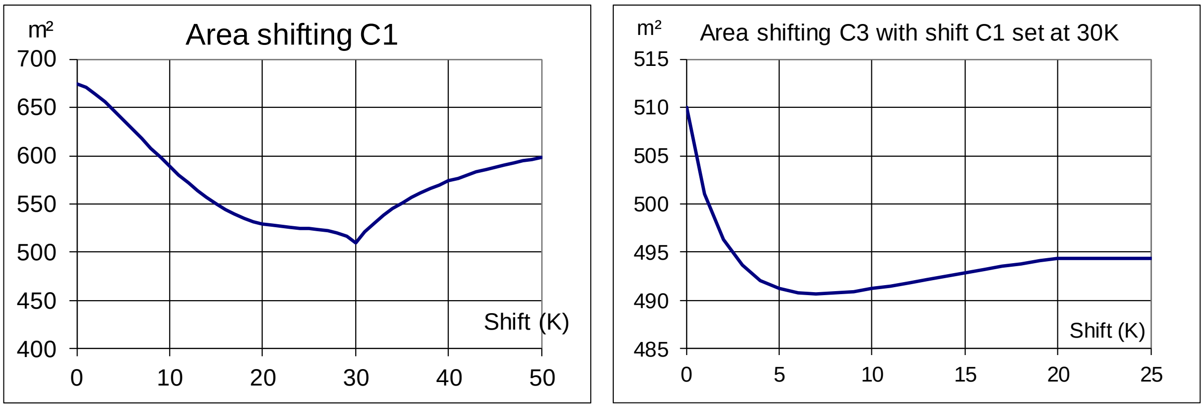
(a) (b)

Figure 1: network generated following rules of classic pinch analysis (a) and optimum network (b)

Crisscross optimisation prior to design is now applied according to the following procedure.

At the start, energy targets are set at a reasonable value; this value can be obtained by application of classic pinch analysis or other techniques. These targets can be adjusted, if suggested by the results of the trade-off process after definition of the DTMin contributions. For this example, energy targets are kept at 1000 kW Heating and 1000 kW Cooling and all DTMin contributions are set at 0 K to start with. All streams are now shifted one by one in order to explore the effect on the surface area. It appears that shifting cold stream C1 has the biggest impact on the reduction of the surface area. Applying a shift from 0 K to 50K on C1 results into an area required as shown in Figure 2(a). There is a clear minimum of 510 m² (with discontinuity in the slope of the curve) for a shift of 30K; this shift value for stream C1 is now retained. All remaining streams are now shifted to explore the additional effect on the area. Applying a shift from 0 K to 25K on cold stream C3 (shifting other streams does not reduce the surface area) results into an area required as shown in Figure 2(b). The area is reduced further from the previous 510 m² to a minimum of 490.7 m² for a shift of 7K and evolves to the final value of 494 m² for a shift of 20K, value for which again there is a discontinuity in the slope of the curve. These particular (optimum) shift values were also shown in Table 1.

A discontinuity in the slope of the curve indicates that a stream is entering or leaving an integration band. The discontinuity in the curve of Figure 2(b) for a shift of 20K for C3 is particularly interesting as illustrated by the trade-off curve, which is shown in Figure 3, where it can be compared with the curve for the classic analysis. For a heating load of 1000 kW, there is a dip in the cost curves due to the lower number of units at that point because of the perfect match between heat loads.



(a) (b)

Figure 2: Evolution of the area as a function of the DTMin contribution (shift) of streams.

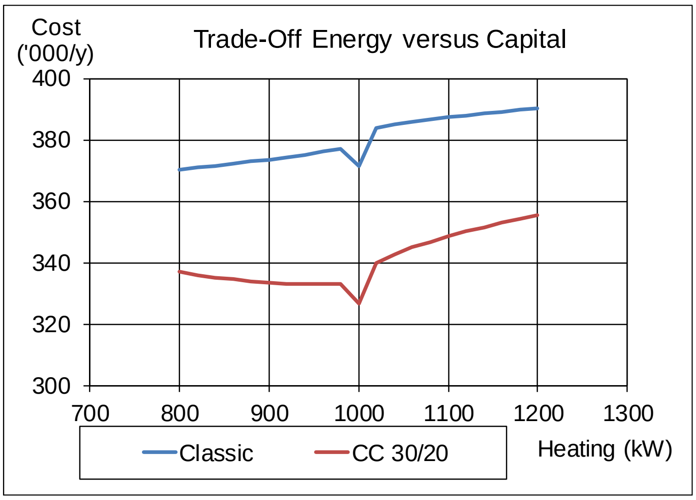


Figure 3: Trade-off between energy and capital.

The analysis generates data sets that now can be used for the design. The grid corresponding to shift values of 30K for C1 and 7K for C3 is shown in Table 2 with the corresponding design in Figure 4(a). This is the design for minimum area with 1000 kW of Heating; it contains 7 units.

The grid corresponding to shift values of 30K for C1 and 20K for C3 is shown in Table 3 with the corresponding design in Figure 4(b). This appears to be the optimum design in terms of minimum cost.

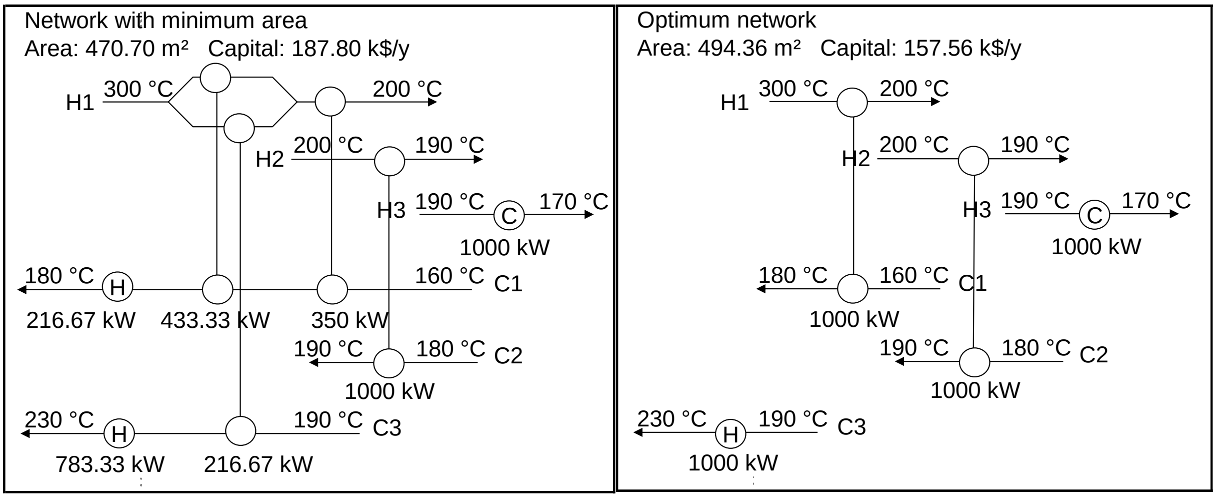
This optimum network of Figure 4(b) can also be obtained by further optimising the network of Figure 4(a) by incremental evolution; no topology trap is hindering such evolution.

Table 2: Stream grid for shift values of 30k for C1 and 7K for C3.

	Shift	U*f													
	K	kW/m²,K	Bands	1		2		3		4		5		6	
Heating		4.00	350.0		350.0		350.0								
H1		0.10					300.0		235.0		200.0				
H2		1.00									200.0		190.0		
H3		1.00											190.0		170.0
C1	30	0.10			180.0		175.7		167.0		160.0				
C2		1.00									190.0		180.0		
C3	7	1.00	230.0		203.0		198.7		190.0						
Cooling		2.00											50.0		30.0

Table 3: Stream grid for shift values of 30k for C1 and 20K for C3.

	Shift	U*f									
	K	kW/m²,K	Bands	1		2		3		4	
Heating		4.00	350.0		350.0						
H1		0.10			300.0		200.0				
H2		1.00					200.0		190.0		
H3		1.00							190.0		170.0
C1	30	0.10			180.0		160.0				
C2		1.00					190.0		180.0		
C3	20	1.00	230.0		190.0						
Cooling		2.00							50.0		30.0



(a) (b)

Figure 4: Networks for minimum area (a) and for minimum cost (b).

The network for minimum area as well as that for minimum cost can both be derived directly from their grid without any further intervention. No other method is known to offer this comfort.

The networks in Figure 1(b) and in Figure 4(b) are identical. Figure 1(b) shows crisscross across the pinch, the design in Figure 4(b) does not since crisscross optimisation has been done during analysis, prior to design. The designs in Figure 4(a) and Figure 4(b) are developed on the basis of vertical heat exchange in their heat integration bands ('superstructures'), which is a significant advantage compared with many other procedures that try to extend the integration beyond the boundaries set by the predefined temperature levels.

A discontinuity in the area picture indicates that a stream is leaving or entering the integration band of other streams. A stream leaving a band means that the heat exchanger network will have one heat exchanger unit less which is interesting from the point of view of minimum cost.

The original classic design of Figure 1(a) cannot be developed into the optimum design of Figure 4(b) because it incorporates a topology trap. This topology trap can be avoided (anticipated) with the crisscross analysis procedure prior to design.

In this example, hot steam H1 was not shifted, although it has a low U value. Cold stream C1 with low U value is shifted as expected, but, unexpectedly, cold stream C3 with a high U value is also shifted. This illustrates that there is not necessarily a direct relation between U values and optimum shifts. Optimum shift values are interdependent and depend also on the shape of the composite curves and the degree of integration. It is obvious that for problems with almost parallel composite curves and very high integration, there will be little room left for further crisscross optimisation.

Example 2.

The procedure is further illustrated with a 7-streams problem, originally treated by Colberg & Morari (1990 [3] and by Yee and Grossmann (1990) [14]; it was also studied by Gcaba (1998) [15] and Anantharaman (2001) [16]. The data are given in Table 4.

Table 4: Data set example 2 (Colberg & Morari)

Tsupply	Ttarget	Heat	Shift	U*f	Description
°C	°C	kW	K	kW/K,m²	-
353	313	392.08	0.0	1.25	H1
347	246	296.03	36.0	0.05	H2
255	80	1078.18	0.0	3.20	H3
224	340	832.76	4.0	0.65	C1
116	303	119.87	11.0	0.25	C2
53	113	457.62	14.0	0.33	C3
40	293	427.57	0.0	3.20	C4
377	377	244.13	0.0	3.50	Heating
20	35	172.60	0.0	3.50	Cooling
Annual Cost Heating : 130/kW Cooling : 20/kW					
Annual HEX cost = 8600 + 670 x A $^{0.83}$					

Energy consumption corresponds with a global DTMin of 20 K. Table 4 has been completed with optimum shift values obtained in the crisscross procedure. In order to reduce the number of integration bands, however, the shift of cold stream C3 was reduced from 50K to 14K with a limited impact on the surface area as mentioned further.

Originally, only investment cost figures were defined; they have been completed here with data for energy cost. The analysis was first made with the energy consumption corresponding with the reported

DTMin of 20K. It should be mentioned however that this value might belong to a local suboptimum as can be concluded from the trade-off curve for classic pinch analysis in Figure 5.

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

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

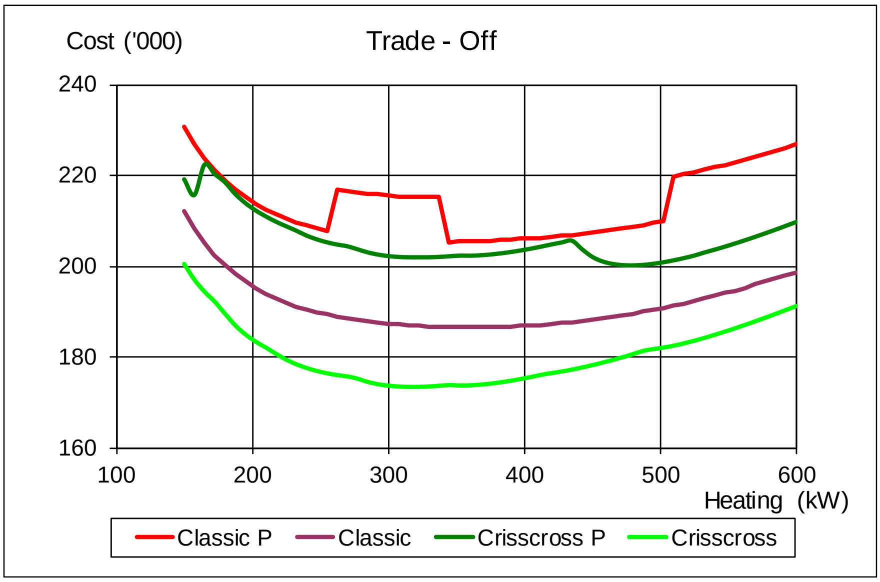


Figure 5: Trade-off Energy versus Capital

The effect of various combinations of stream shifts on the area target is shown in Figure 6. As a result of crisscross, a given integration can be realised with less surface which means that the feasibility area is increased. This can no longer be expressed as a function of DTMin since a uniform DTMin does no longer exist, but now this feasibility area can be shown as a function of the integration or as a function of the hot utility requirement as shown in Figure 7.

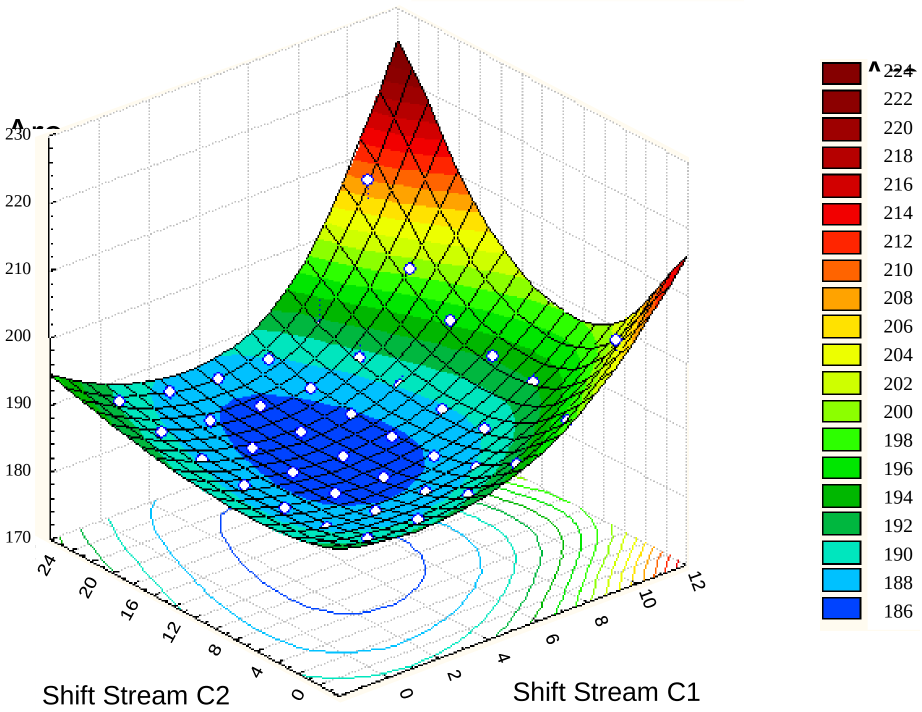


Figure 6: Area as a function of shifts of streams C1 and C2.

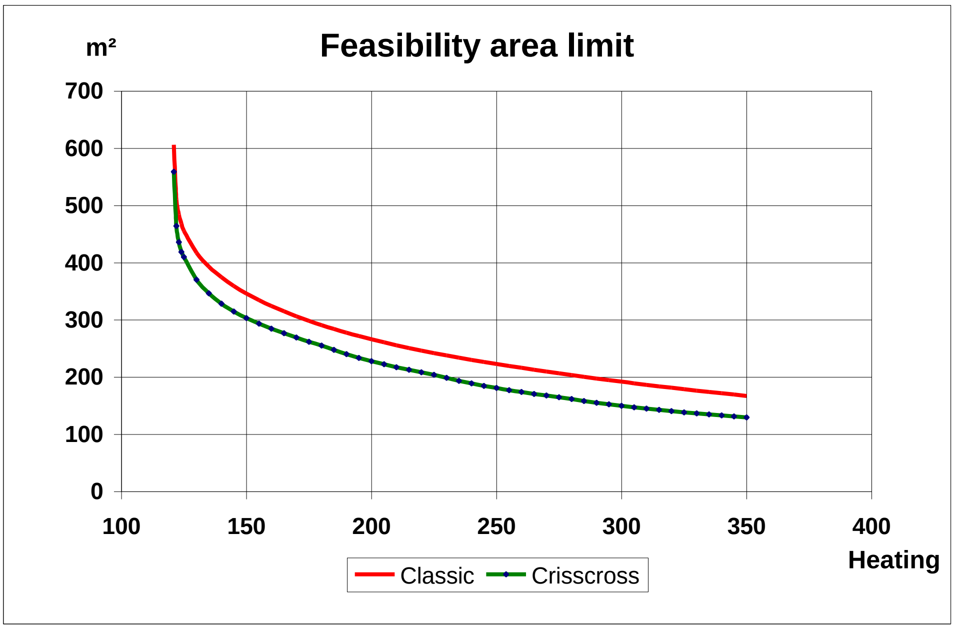


Figure 7: Feasibility area.

Using the grid diagram resulting from the classic pinch analysis leads to the initial network of Figure 8. This initial network shows a topology trap (exchanger X) which cannot be avoided without heavy energy penalty. Indeed, this load below the pinch must be satisfied from the only available hot stream H3 below the pinch whilst exchanger X does not fit into the optimum network as will be shown later.

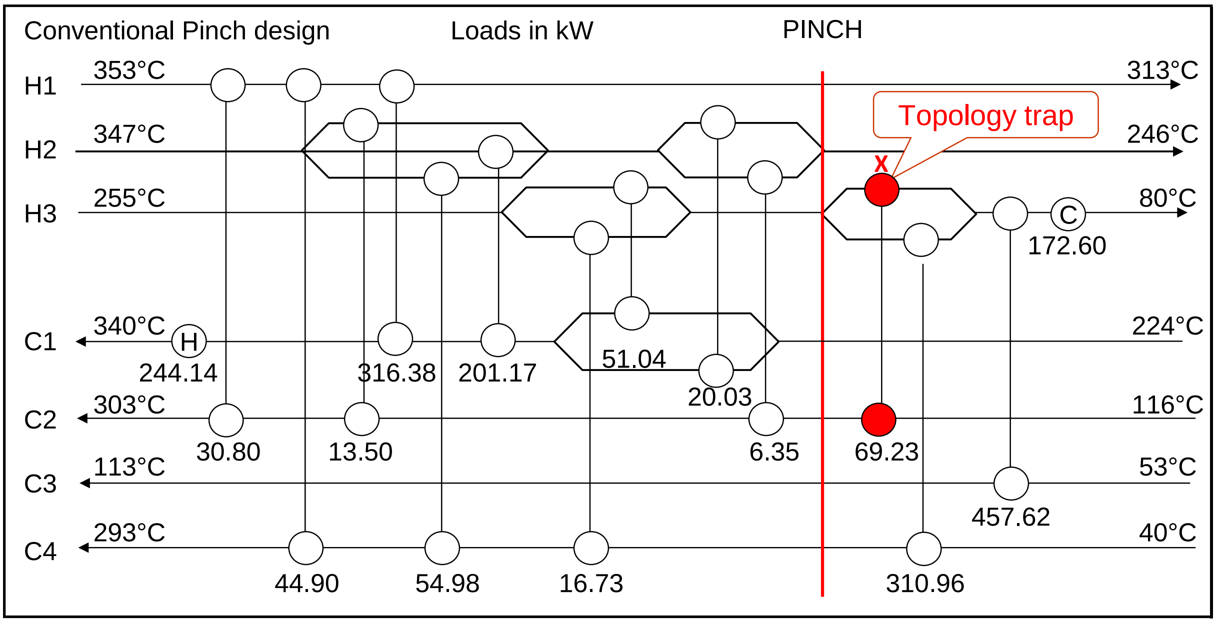


Figure 8: Initial network following conventional pinch design rules.

The crisscross procedure generates a grid diagram as shown in Table 5 containing 11 vertical integration bands (superstructures). With this input, the LP design program calculates an area of 181.97 m² for 24 heat exchangers. This area is lower than what was targeted. Indeed, the area in the targeting procedure is calculated on the basis of a spaghetti network whilst the design program develops a network with minimum area within each band.

Table 5: Grid dataset from the analysis with crisscross.

Grid data set - Output from Heatit																							
Descript	Bands	1		2		3		4		5		6		7		8		9		10		11	
Heating	377.0		377.0		377.0																		
H1					353.0		339.2		313.0														
H2									347.0		291.0		269.3		246.0								
H3											255.0		233.3		210.0		206.2		115.4		108.0		80.0
C1	340.0		310.0		306.3		289.0		262.0		244.8		224.0										
C2			303.0		299.3		282.0		255.0		237.8		217.0		126.2		116.0						
C3																	113.0		53.0				
C4							293.0		266.0		248.8		228.0		137.2		127.0		67.0		40.0		
Cooling																					35.0		20.0

The network obtained could now be further developed by reducing the number of units. It is more appropriate, however, to reduce the number of integration bands as far as possible by merging adjacent bands prior to structuring the flow sheet of the network. This is possible as long as there are no temperature constraints (the design program assumes isothermal split). If merging of bands is no longer possible, then small heat exchangers can be merged individually with units on the same process streams in the integration band upstream or downstream. Finally, heat exchange for a particular stream in a particular band can be blocked by imposing identical input and output temperatures on that stream. By using one or more of these techniques the number of integration bands (superstructures) can be reduced to 7 leading to the initial network of Figure 9 with 16 exchangers.

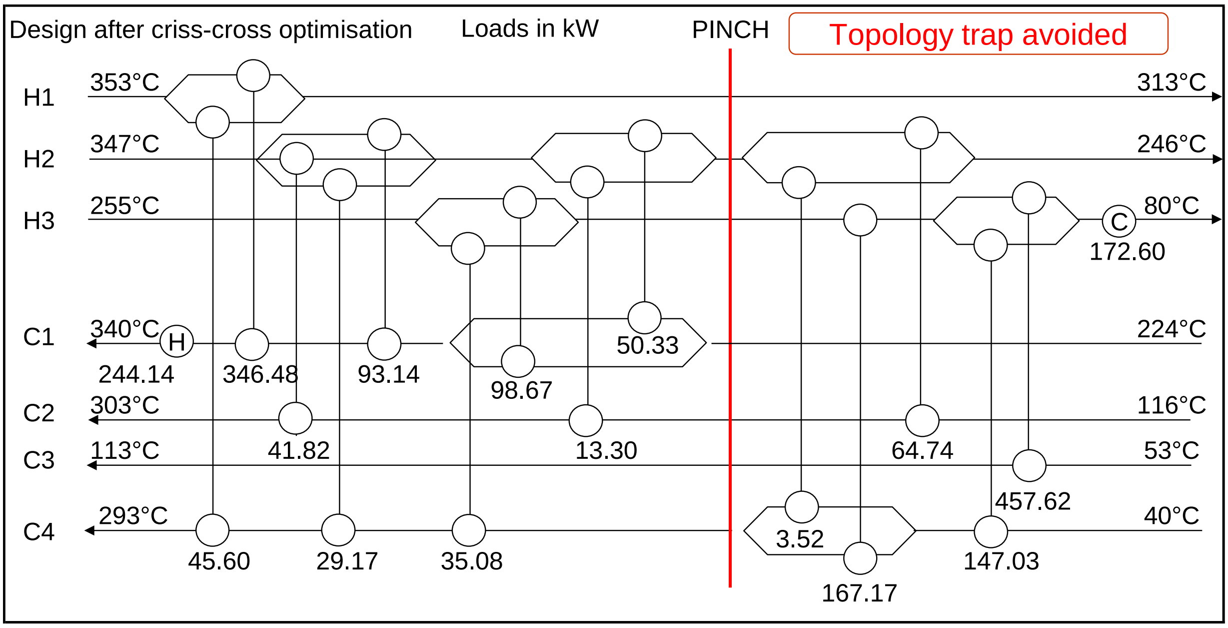


Figure 9: Initial network from the grid with the crisscross procedure.

Contrary to the network in Figure 8, this initial network shows no topology traps. Reducing the number of integration bands further to 6 leads to the grid diagram as shown in the Table 6 and to the initial network of Figure 10 with 10 exchangers. This network can be further developed into the network of Figure 11 using incremental evolution and Smart nodes [17]; the cost is 183.05 k$ (the remaining split on hot stream H1 has been undone manually leading to a further marginal improvement of 0.015%).

This network is identical with the network developed by Anantharaman and Gundersen using a combination of LP, NLP and MILP procedures [16].

Table 6: Grid with reduced number of bands.

Grid dataset after development													
Description / Bands		1		2		3		4		5		6	
Heating	377.0		377.0										
H1			353.0		313.0								
H2					347.0		246.0						
H3							255.0		233.9		108.0		80.0
C1	340.0		306.0		261.8		237.3		224.0				
C2					303.0		116.0						
C3									113.0		53.0		
C4			293.0		248.8		248.8		228.0		40.0		
Cooling											35.0		20.0

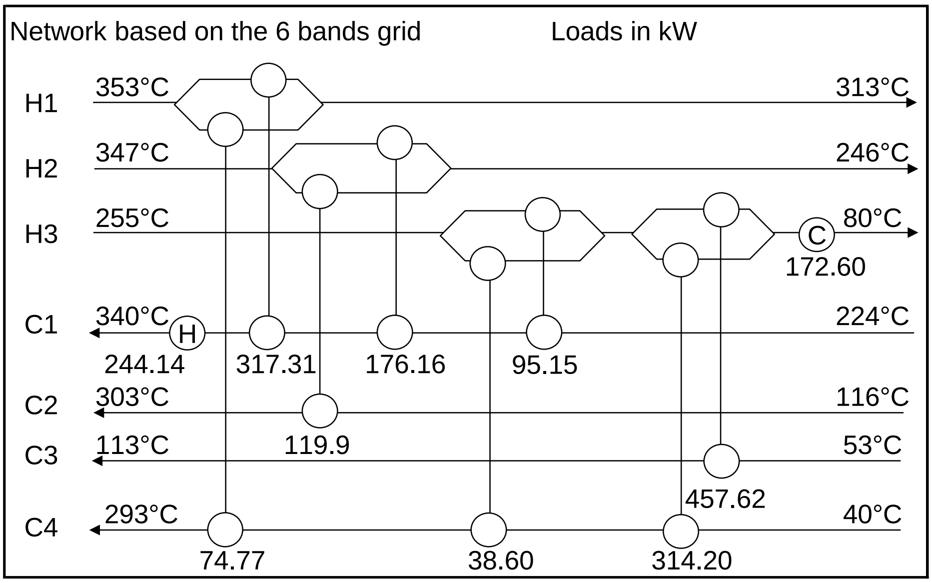


Figure 10: Initial network on the basis of the 6 bands grid.

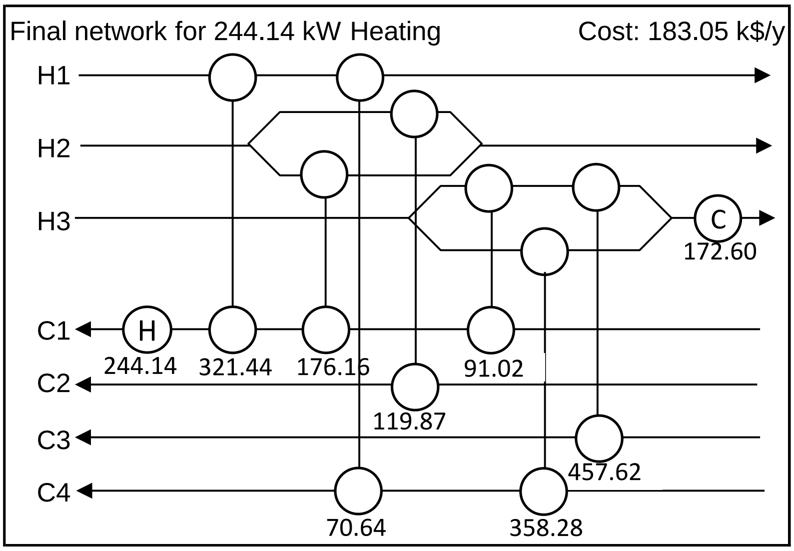


Figure 11: Final network for 244.14 kW Heating after evolution and optimisation.

The size of a problem can often be reduced by applying heuristic rules to start with. “Satisfy the smallest heat load with one single heat exchanger” is very appropriate in this case, defining the crucial match between hot stream H2 and cold stream C2 in the optimum network in Figure 11 from the very beginning. However, according to classic pinch analysis, this choice would have to be rejected, since the remaining problem would show an energy penalty of 69.23 kW, which is in line with the unavoidable topology trap in Figure 8. On the other hand, analysis with crisscross optimisation shows no penalty and, so, would endorse the choice of said match.

The shape of the trade-off “Crisscross P” curve” in Figure 5 would suggest that a Heating load of 480 kW, respectively 340 kW would also deserve special attention. Further analysis and design for the 480 kW cost minimum leads to the network of Figure 12 (best of various options) with 2 independent systems, 7 units and an annual cost of 177.97 k$ at 440.68 kW Heating.

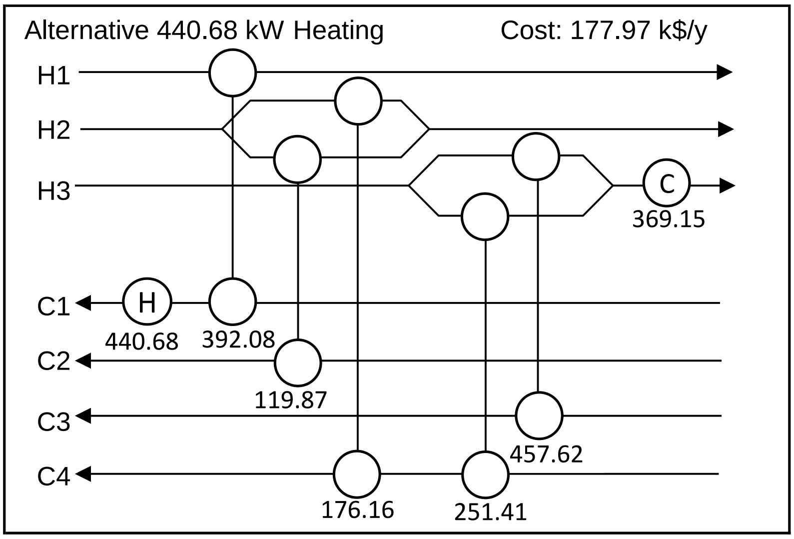


Figure 12: Network for 440.68 kW Heating

Further analysis for the 340 kW cost minimum leads to a reduced grid of Table 7.

Table 7 – Reduced grid for a Heating of 340 kW.

Grid dataset after development													
Description / Bands		1		2		3		4		5		6	
Heating1	377.0		377.0										
H1			353.0		313.0								
H2					347.0		312.0		246.0				
H3							255.0		250.0		123.6		80.0
C1	340.0		292.6		248.8		241.1		224.0				
C2					303.0		230.1		116.0				
C3									113.0		53.0		
C4			293.0		247.1		247.1		230.0		40.0		
Cooling1											35.0		20.0

This leads to the network of Figure 13 with 8 units and an annual cost of 175.59 k$ at 335.74 kW Heating. This cost is 4.1 % lower than the cost of the network in Figure 11. Admittedly, the network in Figure 13 has one additional split, the cost of which has not been considered. The splits, however, can easily be undone, leading to the set of networks of Table 8. The network without splits is shown in Figure 14.

Table 8: Optimum networks

No match between H2 and C4						
Heating	Area	# HEX	Energy	Capital	Total	Splits
kW	m²	-	k$/y	k$/y	k$/y	-
335.77	153.29	8	48.93	126.66	175.59	H1, H2, H3
335.85	153.22	8	48.95	126.71	175.66	H2, H3
333.23	155.74	8	48.55	127.43	175.98	H2
333.23	183.61	8	48.55	134.26	182.81	-

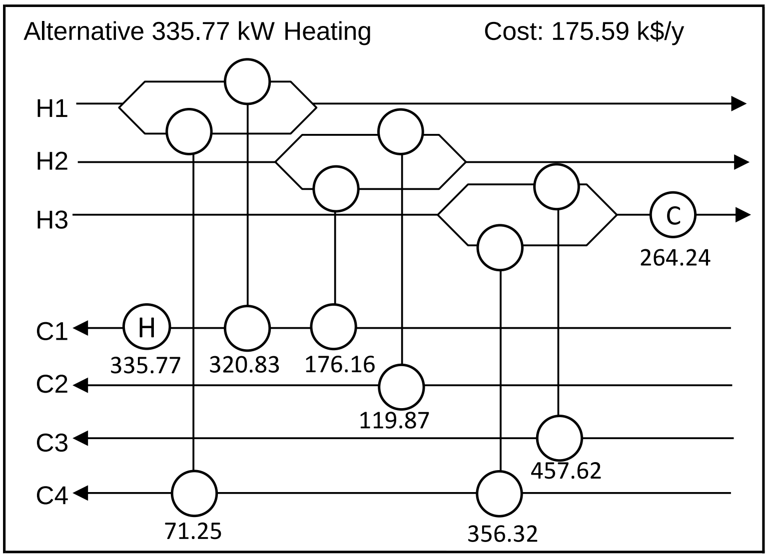


Figure 13: Network for 335.74 kW Heating.

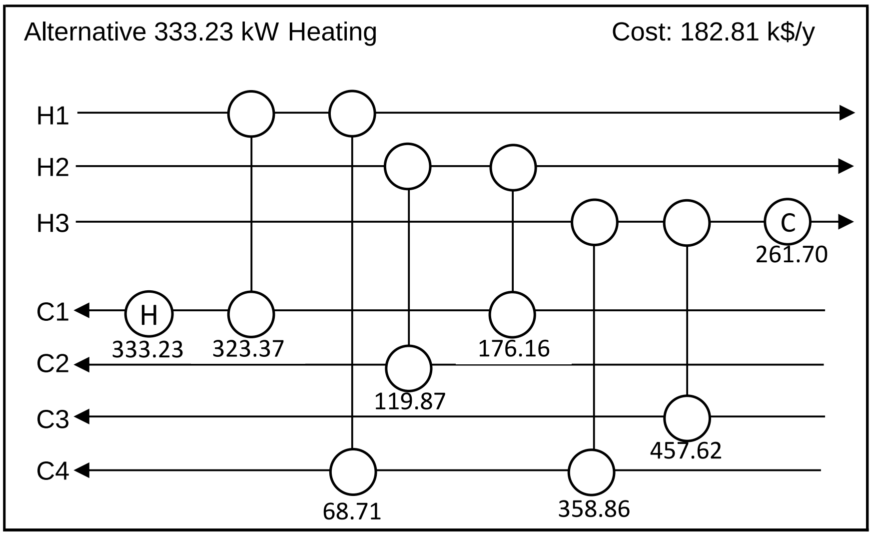


Figure 14: Optimum network without splits.

The grid in Table 7 leads to networks that have no match between hot stream H2 and cold stream C4. Alternative networks with no match between hot stream H1 and cold stream C4 can be developed on the basis of the grid in Table 9.

Table 9 – Alternative grid with reduced number of bands.

Grid dataset after development													
Description / Bands		1		2		3		4		5		6	
Heating1	377.0		377.0										
H1			353.0		313.0								
H2					347.0		246.0						
H3							255.0		250.0		123.6		80.0
C1	340.0		292.6		238.0		228.3		224.0				
C2					303.0		116.0						
C3									113.0		53.0		
C4					293.0		230.0		230.0		40.0		
Cooling1											35.0		20.0

This leads to the network of Figure 15 with 8 units and an annual cost of 176.79 k$ at 314.36 kW Heating. This network has 2 splits which, however, can easily be undone, leading to the second set of networks of Table 10. This second set of networks needs 5% less heating than the first set.

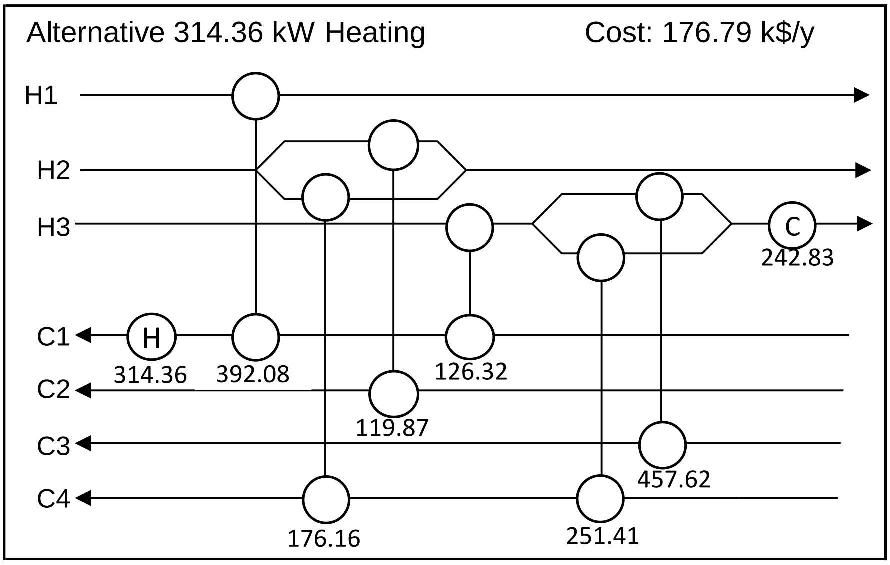


Figure 15 – Network for a Heating of 314.36 kW

Table 10 – Second set of networks.

No match between H1 and C4						
Heating	Area	# HEX	Energy	Capital	Total	Splits
kW	m²	-	k$/y	k$/y	k$/y	-
314.36	164.22	8	45.72	131.06	176.79	H2, H3
315.48	167.46	8	45.89	131.99	177.89	H2
315.48	216.76	8	45.89	144.34	190.23	-

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

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