Pinch analysis with crisscross optimization prior to design

Heat exchanger network synthesis based on optimized input data sets

Example Case 2

Example from Gundersen and Grossmann

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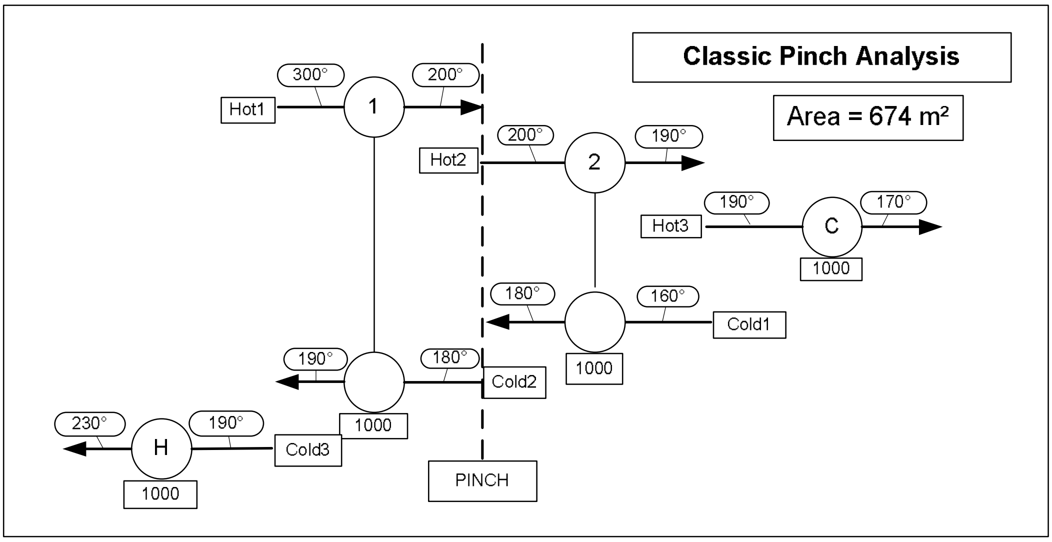
Case 2 is a 6 streams example taken from Gundersen and Grossmann. The data set is shown in Table 2.1. The example was produced in the mid eighties to illustrate the weaknesses of (classic) pinch analysis.

Table 2.1

Data example Gundersen and Grossmann							
						Optimum shift for	
		Classic pinch analysis				Minimum	Minimum
Tsupply	Ttarget	Heat	DTmin	U*f	Descript.	Area	Cost
°C	°C	kW	K	kW/K,m²	-	K	K
300	200	1000	10.0	0.10	H1	0	0
200	190	1000	10.0	1.00	H2	0	0
190	170	1000	10.0	1.00	H3	0	0
160	180	1000	10.0	0.10	C1	30	30
180	190	1000	10.0	1.00	C2	0	0
190	230	1000	10.0	1.00	C3	7	20
Targets							
350	350	1000		4.00	Heating		
30	50	1000		2.00	Cooling		

Energy targets for an overall DTMin of 20 K are 1000 kW Heating and 1000 kW Cooling. The classic pinch design is shown in Fig.2.1; the surface area is 674 m².

Fig.2.1



The optimum design is shown in Fig.2.2 with an area of 494 m². Classic pinch analysis fails to produce the optimum result.

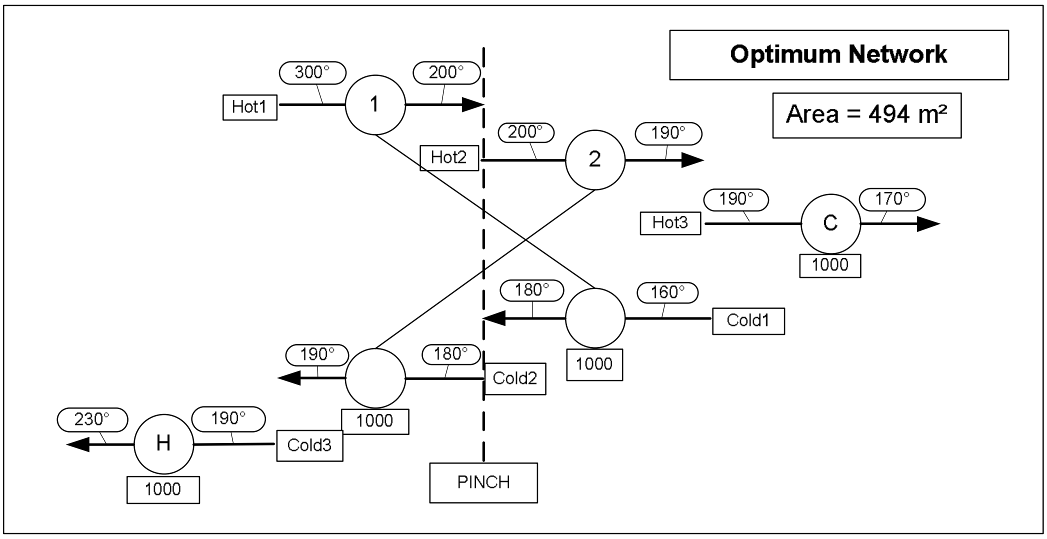


Fig.2.2

An attempt to solve the problem in a structured way using the ódiverse pinchôconcept was reported by Rev & Fonio. One intermediate result (the ópreferred candidateô) is shown in Fig.2.3 from which the optimum design can be developed by appropriate evolution. The procedure leading to the intermediate result, however, is complex and not straightforward. It would seem therefore that also sophisticated computer programs fail to produce the optimum solution in a simple way.

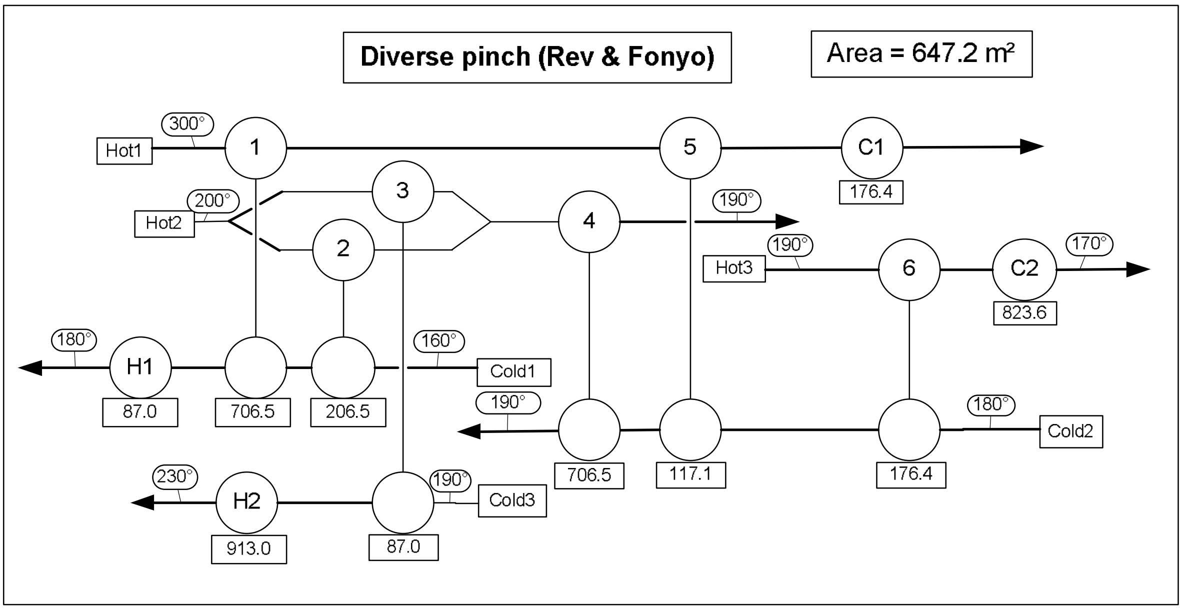


Fig.2.3

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

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 Fig.2.4. 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 Fig.2.5. 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 are also shown in Table 2.1.

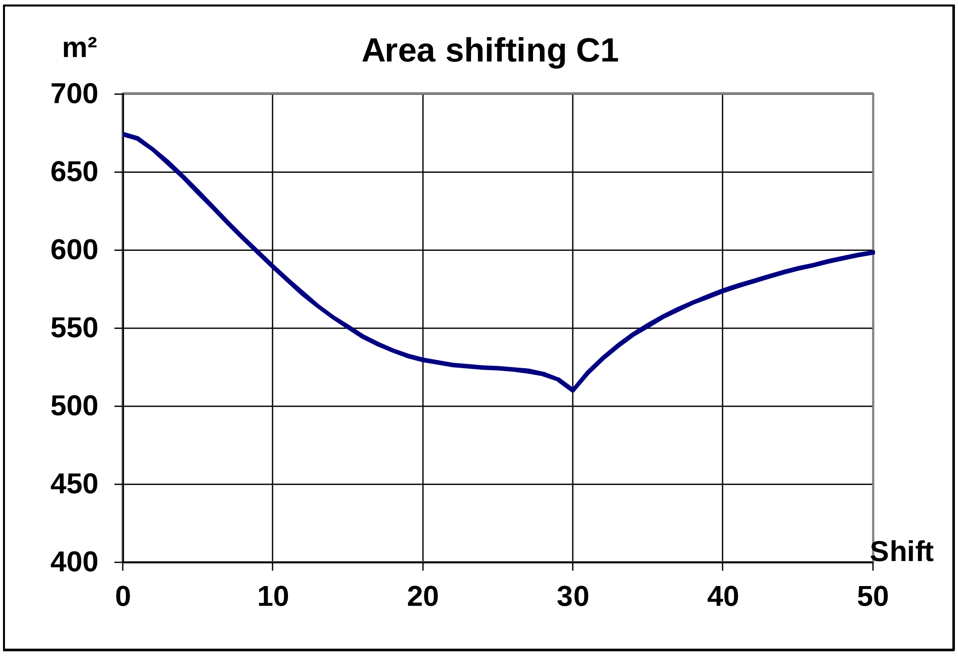


Fig.2.4

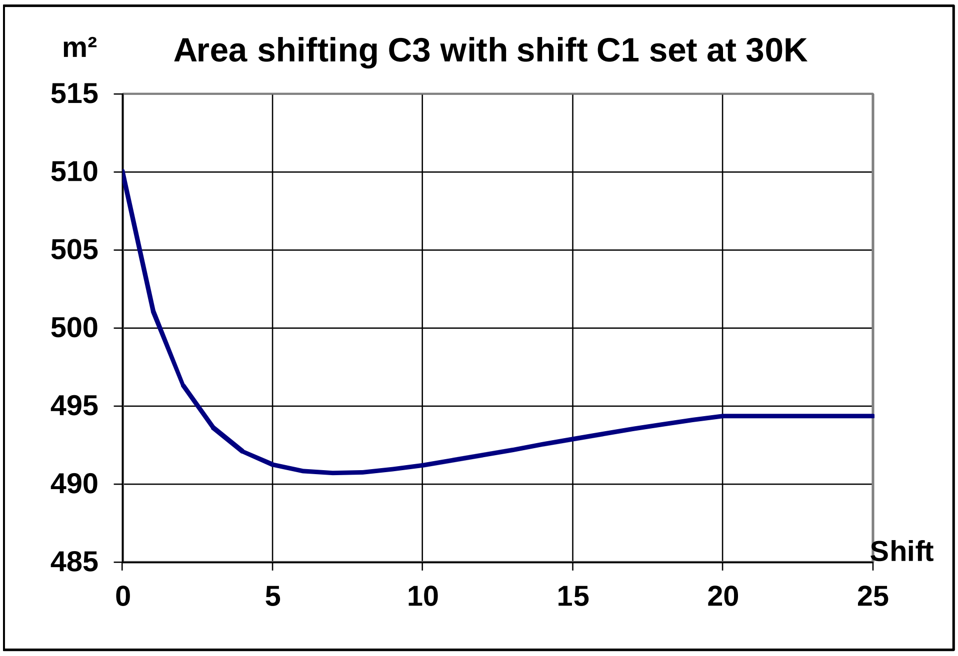


Fig.2.5

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 Fig.2.5 for a shift of 20K for C3 is particularly interesting as illustrated by the corresponding cost curve in Fig.2.6.

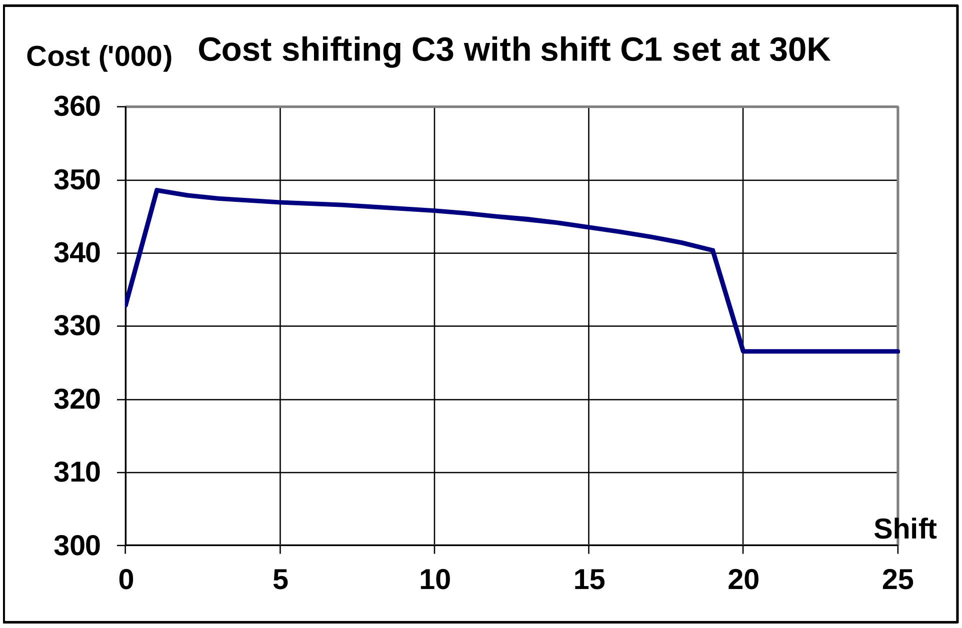


Fig.2.6

The corresponding trade-off curve is shown in Fig.2.7 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 as a consequence of the perfect match between heat loads.

Fig.2.7

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 2.2 with the corresponding design in Fig.2.8. This is the design for minimum area with 1000 kW of Heating; it contains 7 units.

Table 2.2

	Shift K	U*f 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

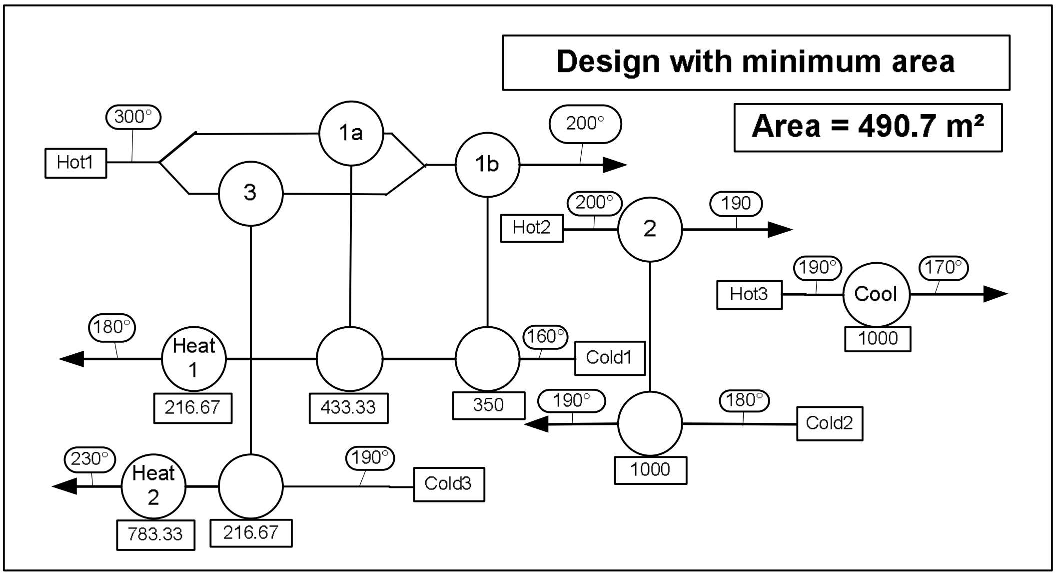


Fig.2.8

The grid corresponding to shift values of 30K for C1 and 20K for C3 is shown in Table 2.3 with the corresponding design in Fig.2.9. This appears to be the optimum design in terms of minimum cost.

Table 2.3

	Shift K	U*f 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

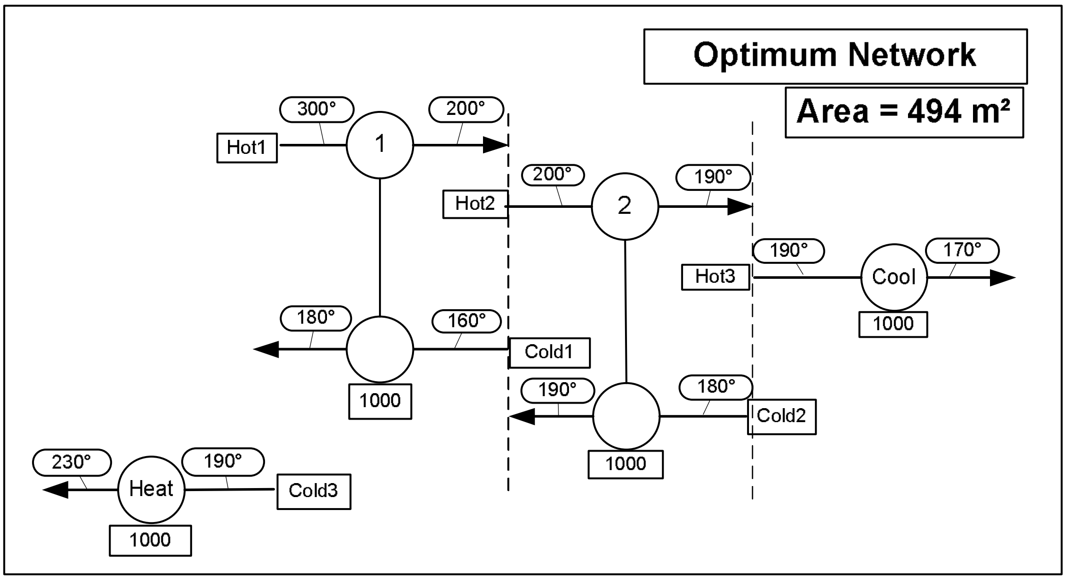


Fig.2.9

This optimum design could also be obtained by further optimizing the network of Fig.2.8 by eliminating exchanger # 3 by simple incremental evolution of the network; no topology trap is hindering the evolution.

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

The designs in Fig.2.2 and in Fig.2.9 are identical. Fig.2.2 shows crisscross across the pinch, the design in Fig.2.9 does not since crisscross optimization has been done during analysis, prior to design. The designs in Fig.2.8 and Fig.2.9 are developed on the basis of vertical heat exchange in the 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 Fig.2.1 cannot be developed into the optimum design of Fig.2.9 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 value and optimum shift.

Fig. 2.10 shows for a Heating target of 600 kW the result of shifting hot stream H1 between 0K and 20K with shift values of cold stream C1 set at respectively 14K, 15K, 16K and 17K. In this case, contrary to the previous data set, hot stream H1 has to be shifted. Obviously, optimum shift values also depend upon the degree of integration. It will not be a surprise that with rather parallel hot and cold composite curves and a very high degree of integration there will be no room left for crisscross.

Fig.2.10