Pinch Analysis with crisscross optimization prior to design

Example treated by Ahmad, Zamora, Bogataj, Rev & Fonio, Zhu et al., Serna et al.

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Example case 13 has been treated many times and is interesting for several reasons: the temperature level of the hot utility is not the highest level in the system and has a low heat transfer coefficient, the heat transfer coefficients of the various process streams are not the same and the stream data set has been explored with small heat loads, with mid-size heat loads and with large heat loads (the latter, however, with heat transfer coefficients that are different from the other cases). This example problem is also interesting because it was defined as one of the most difficult practical problems for targeting purposes (Jegede and Polley, 1992).

The data set for the mid-size problem that is studied here is given in Table 13.1 with shift values optimized with the crisscross procedure for minimum surface area. The heating load has been chosen on the basis of the trade-off, illustrated in Fig.13.1, ñCrisscross ï 1 systemò and would correspond with an overall DTMin of 35.6°C in classic pinch analysis.

Table 13.1

Tsupply	Ttarget	Heat	Shift	U*f	Description
°C	°C	kW	K	kW/m²,K	-
159	77	1873.70	8.0	0.10	H1
267	80	381.48	19.0	0.04	H2
343	90	1361.14	-1.0	0.50	H3
26	127	942.33	63.0	0.01	C1
118	265	2882.67	0.0	0.50	C2
300	299	1675.00	46.0	0.05	Heating
20	60	1466.32	0.0	0.20	Cooling

Hot utility = 110 EUR/kW,year Cold utility = 10 EUR/kW,year

HEX cost formula = 874.0 + 438.15*Area $^{0.78}$

The various shift contributions have been optimized for the heat load corresponding with the cost minimum in the Trade-off curve; away from that minimum, however, shift contributions would have to be adjusted, leading to a Trade-off curve, specific for that particular load. The ultimate Trade-off curve is then the envelope of those particular individual curves and that envelope curve is slightly flatter than the curve shown on the graph. The minimum of that curve, however, is the one as withheld.

Classic algorithms for the area targeting never produced satisfactory results because of the large differences in heat transfer coefficients and various efforts have been undertaken already since the early eighties to develop more adequate procedures for the area targeting purpose: Nishimura in

1980, Ahmad in 1986, Rev and Fonio in 1990, Serna-Gonzales in 2004. In Table 13.3, the results of some of these works are compared with the results obtained by applying crisscross optimization prior to design (results ñHeatitò) and after the latter have been further optimized with LP in the different vertical integration bands, resulting into a minimum number of units in each band simultaneously with achieving minimum area in each band (results ñDesignitò). It appears from the comparison that the optimum design is even out of the range of heat loads, considered in earlier studies. The reason could be that classic pinch analysis suggested an optimum DTMin at around 30 K, after which the cost curve goes up and only drops back at a DTMin of 45 K. Very often, however, as also in this case, the discontinuities (jumps and falls) in the trade-off curve are artificial and are caused by the rigorous request of splitting the HEN into two networks, one above and one below the pinch. One could argue that the discontinuities are caused by the analyst himself rather than by the characteristics of the process.

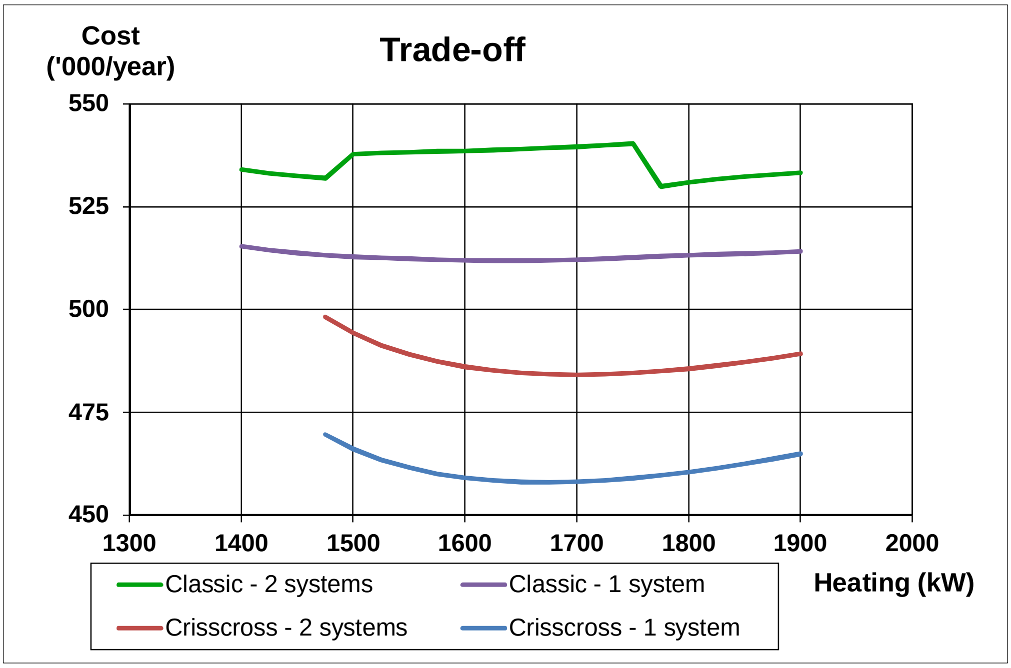

Fig.13.1

The results in Table 13.3 show that the approach with the crisscross optimization procedure leads to results that are better than with previous attempts. For the heat load as specified in the targeting stage, surface area would be 2101.73 m²; the Bath formula would calculate 2690.82 m². The average deviation in costs between achievable designs and targets is no more than 0.5% over a broad range of investigated heat loads.

The grid diagrams resulting from classic pinch analysis and from the crisscross procedure are shown in Table 13.4. The original grids with respectively 11 and 10 vertical integration bands can be simplified and reduced to 6 bands without affecting the nature of the problem.

When merging adjacent bands, the results can be assessed in terms of area, number of HEX units and cost and in case of various alternatives, the most cost effective one can be withheld.

From the grid diagram of the classic approach, it is clear that a Heater will be allocated to cold stream C2 only. In the Crisscross case, a Heater will be put on cold stream C2 and also on C1 because C1 and the Heating utility have come into a common integration band. The final designs of both approaches are shown in Fig.13.2 and Fig.13.3. The optimum design shows that, indeed, a Heater is required on both cold streams C1 and C2.

The optimum design with 9 units of Fig. 13.3 can be further simplified into the design of Fig. 13.4 with 8 units with a negligible cost penalty.

Analysis of the differences between the classic and the crisscross approach and of the impact of different starting values for the initial network leads to the following insight.

The optimum HEN shows a Heater on C1 and a Cooler on H3, each of which might be missing following the classic approach.

A Heater will appear on cold stream C1 only if crisscross is applied to such an extent that Heating utility and C1 come into a common integration band. Referring to Table 13.3 where shift values are optimized for minimum area, a Heater will appear on C1 for heating loads of 1400 kW onwards. The trade-off suggested a heating load of 1675 kW and, indeed, this input generates a Heater on C1 in the initial network.

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

Knowing that the optimum design needs a Cooler on H3, expectedly, forcing a Cooler on H3 by moving out C1 from the cooling band manually could bring us closer to the optimum design. This was done for Heating loads of 1800 kW and 1620 kW, two near optimum values in the trade-off for the classic approach. Further, a simple optimization procedure was applied: starting with the original Heating loads, network parameters such as intermediate temperatures and stream split ratios are changed incrementally in order to achieve lower cost. The results are shown in Fig.13.5 and 13.6. This illustrates the non-convexity of the problem, as a consequence of which the procedure ends up in different local sub-optima. It might be interesting to know that, sometimes, the shape of the solution space can be changed favorably by pulling down the optima by reducing the area exponent c in the cost formula. Starting with a Heating load of 1800 kW and applying said procedure would also lead to the solution of Fig.13.6.

The example case described illustrates the benefits of the crisscross procedure in the analysis stage, generating an optimum data set for synthesis of an initial network. The applied procedures lead to better networks than those developed by other authors applying either LP or using the diverse pinch method.

Table 13.3

Area				**Opt. Design**							
Targeting	DTMin conventional	K	35.6		30	25	20	15	10	5	1
	Heating	kW	1675.00	**1621.14**	1456.72	1358.67	1260.62	1162.57	1064.52	966.47	888.03
	Cooling	kW	1466.32	**1412.46**	1248.04	1149.99	1051.94	953.89	855.84	757.79	679.35
	Optimum DTshift contributions										
	H1	K	8.0	7.0	6.0	5.5	5.0	4.5	3.8	4.2	0.7
	H2	K	20.0	18.0	15.5	14.5	13.0	12.0	10.9	9.0	2.0
	H3	K	-1.0	-1.0	-1.0	-1.0	-1.0	-0.5	-0.8	-0.5	0.0
	C1	K	63.0	60.0	50.0	43.0	36.0	30.0	23.4	22.2	15.6
	C2	K	0.0	0.0	0.0	0.0	0.0	0.5	1.7	0.4	0.4
	Heating	K	46.0	46.0	46.0	41.5	41.0	41.3	40.6	41.3	34.5
	Cooling	K	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Area	Bath formula	m²	2690.82	2762.85	3006.39	3185.92	3415.07	3719.97	4154.61	4873.11	6334.31
	Rev & Fonio	m²			2894.31	3160.81	3418.43	3723.47	4156.38	4868.56	6279.21
	Serna & Jimenez	m²			2486.75	2709.92	2976.88	3314.34	3749.74	4414.57	5835.40
	LP Ahmad	m²			2330.00	2500.00	2900.00	3150.00	3550.00	4230.00	5740.00
	Declercq										
	Heatit	m²	2101.73	2175.66	2460.80	2687.52	2956.52	3293.47	3720.74	4431.30	5799.06
	Designit	m²	2040.89	2111.44	2386.29	2605.86	2873.58	3210.05	3652.89	4365.21	5724.17
	Designit + opt	m²	1995.45		2339.68			3179.78			5716.66
Cost											
Targeting	Bath formula	'000	539.16	538.66	532.17	535.98	543.84	557.82	582.11	628.63	733.81
	Declercq										
	Heatit (2 systems)	'000	484.16	485.13	493.02	502.26	514.28	530.69	551.24	592.96	692.58
	Heatit (1 system)	'000	457.92	458.39	464.95	473.60	485.58	502.90	527.09	573.19	669.78
HEN design											
	Declercq										
	Optimum Design	'000	461.02	**460.72**	465.77	475.37	482.78	501.54			675.84
	Area optimum design	m²	2156.02	**2255.60**	2480.63	2710.68	2869.01	3265.57			5964.87
	# units		9	**9**	9	9	10	11			12
Deviation Optimum Design versus Target (%)			0.7%	0.5%	0.2%	0.4%	-0.6%	-0.3%			0.9%

Table 13.4 ï Grid diagrams

Process : 3H+2C **Version : Classic**

	area	#HEX	AreaCost
Heatit	2690.82	6	312.94
Design	2733.33	14	340.98

N°	Tsupply °C	Ttarget °C	Heat kW	Shift K	Description -	U*f kW/m²,K	Bands						
							1	2	3	4	5	6	
6	300	299	1675.00		Heating	0.05		300.00	299.00				
1	159	77	1873.7		H1	0.10					159.00	138.43	77.00
2	267	80	381.5		H2	0.04			267.00	183.13	159.00	138.43	80.00
3	343	90	1361.1		H3	0.50	343.00	299.00	299.00	183.13	159.00	138.43	90.00
4	26	127	942.3		C1	0.01				127.00	126.72	60.00	26.00
5	118	265	2882.7		C2	0.50	265.00	252.93	167.51	127.00	118.00		
7	20	60	1466.32		Cooling	0.20						60.00	20.00

Process : 3H+2C **Version : Crisscross**

	area	#HEX	AreaCost
Heatit	2101.73	6	259.01
Design	2012.37	14	291.85

N°	Tsupply °C	Ttarget °C	Heat kW	Shift K	Description -	U*f kW/m²,K	Bands						
							1	2	3	4	5	6	
6	300	299	1675.00	46.0	Heating	0.05		300.00	299.00				
1	159	77	1873.7	8.0	H1	0.10				159.00	137.68	126.64	77.00
2	267	80	381.5	20.0	H2	0.04			267.00	171.00	149.68	140.74	80.00
3	343	90	1361.1	-1.0	H3	0.50	343.00	252.00	252.00	150.00	128.68	128.68	90.00
4	26	127	942.3	63.0	C1	0.01		127.00	77.30	77.30	55.00	26.00	
5	118	265	2882.7	0.0	C2	0.50	265.00	240.03	178.27	140.30	118.00		
7	20	60	1466.32	0.0	Cooling	0.20						60.00	20.00

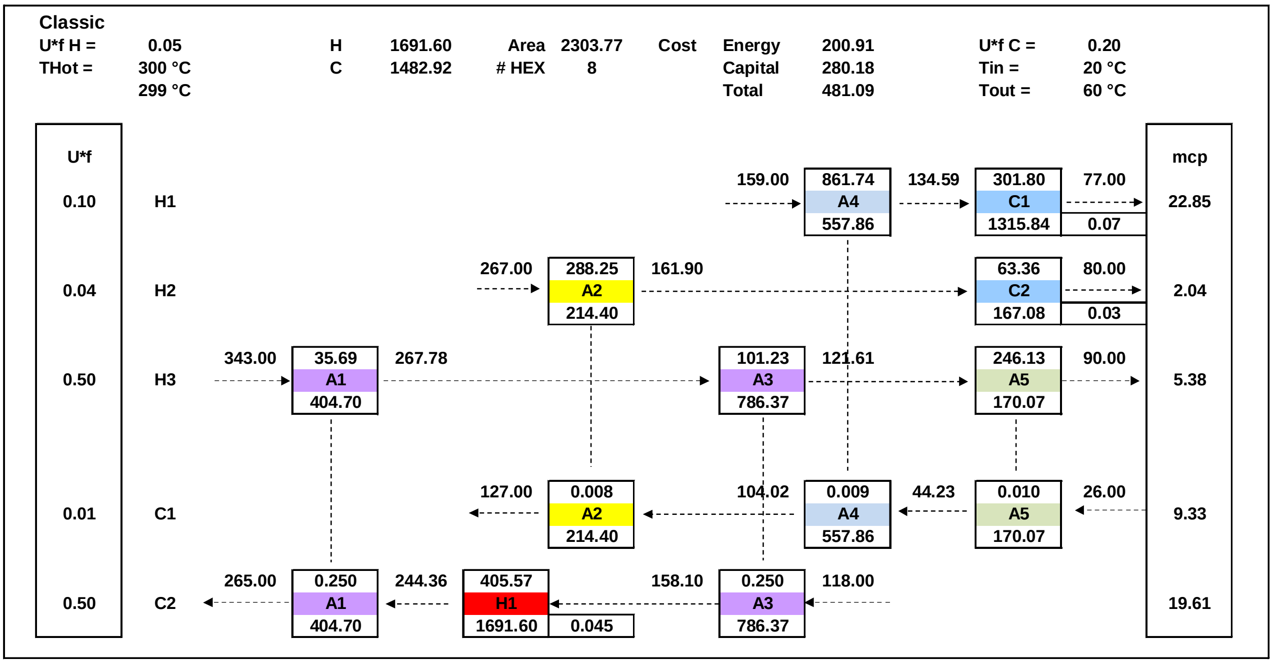

Fig.13.2 ï Result with classic approach

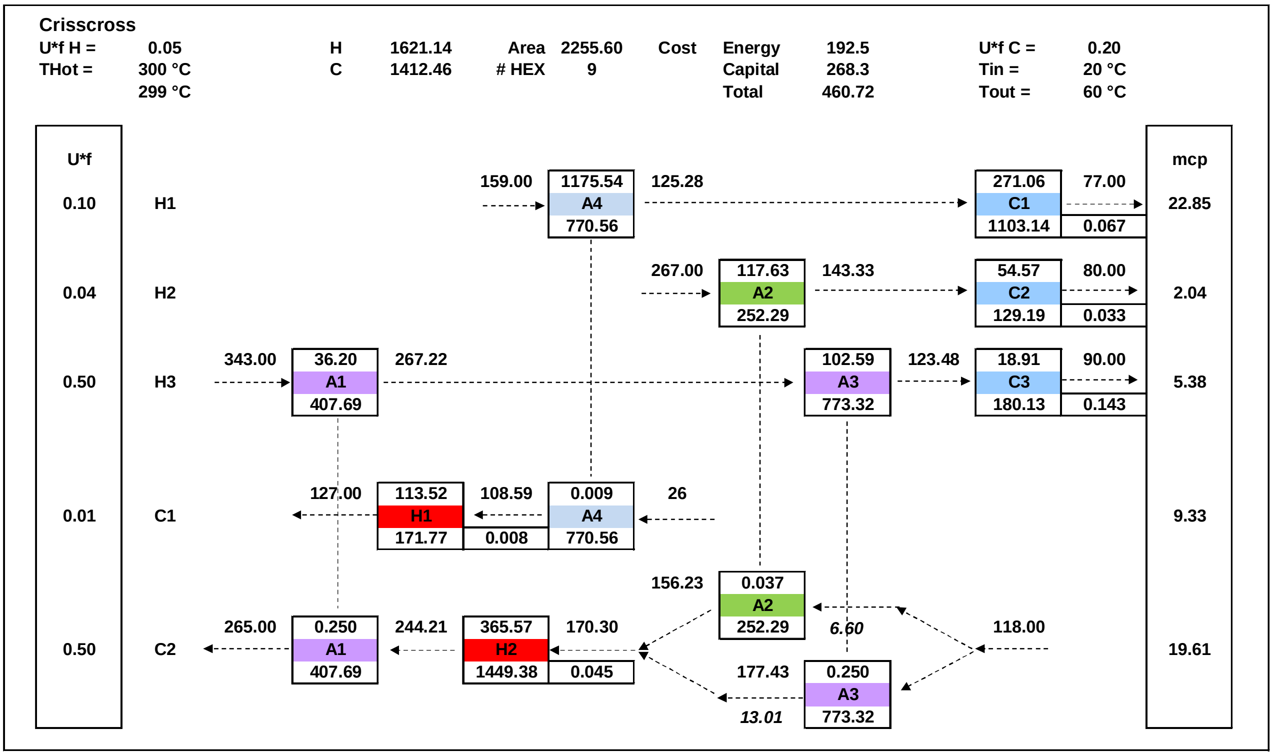

Fig.13.3 ï Result with crisscross optimisation prior to design ï Optimum network

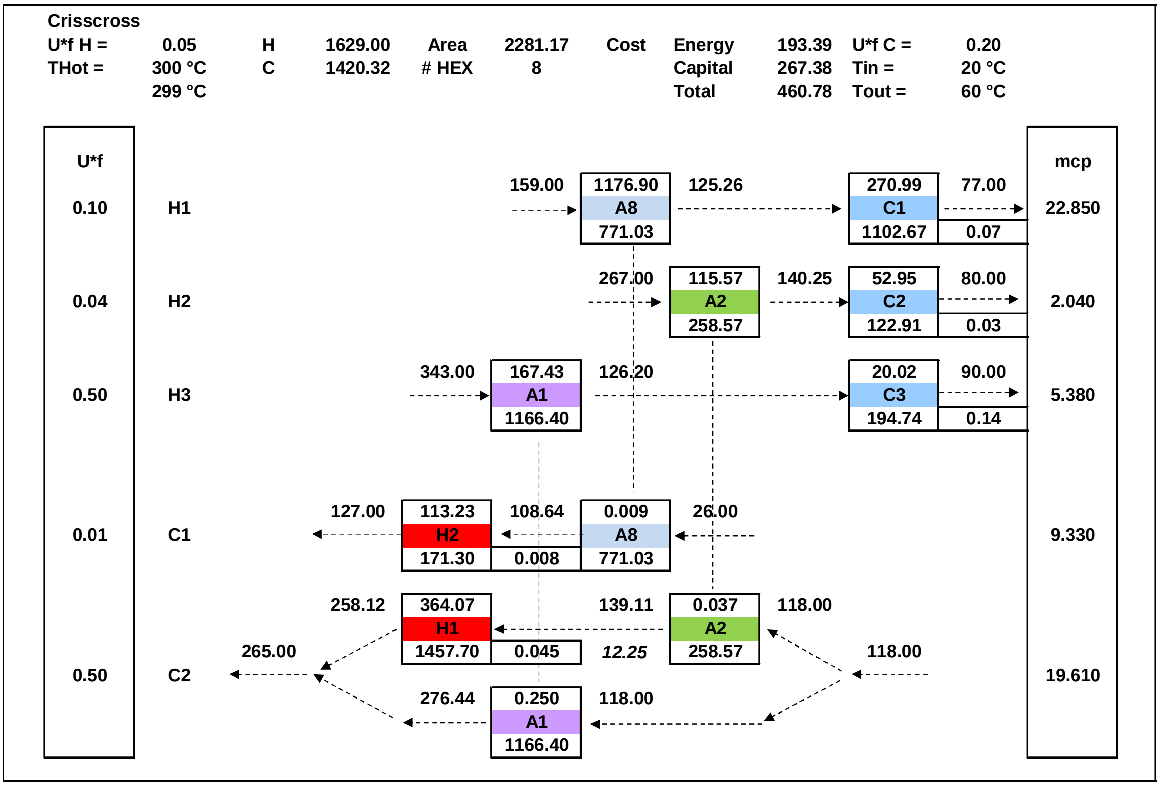

Fig.13.4 ï Optimum network simplified

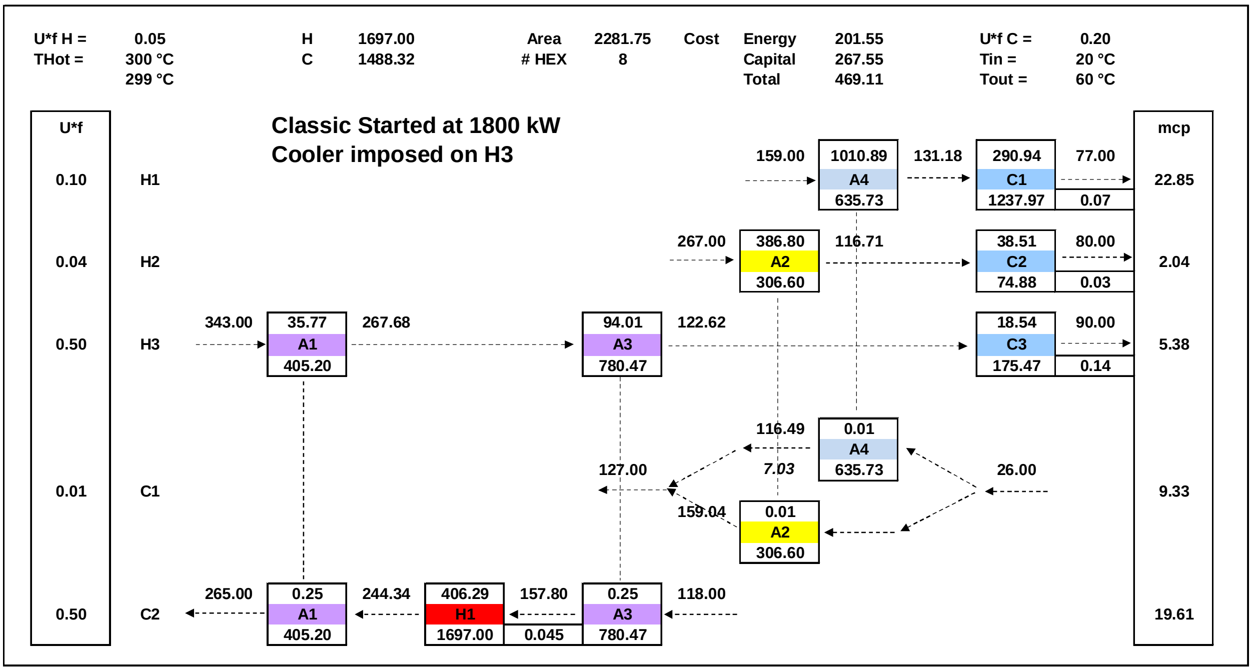

Fig.13.5 ï Result with classic approach ï Starting at 1800 kW Heating ï Cooler imposed

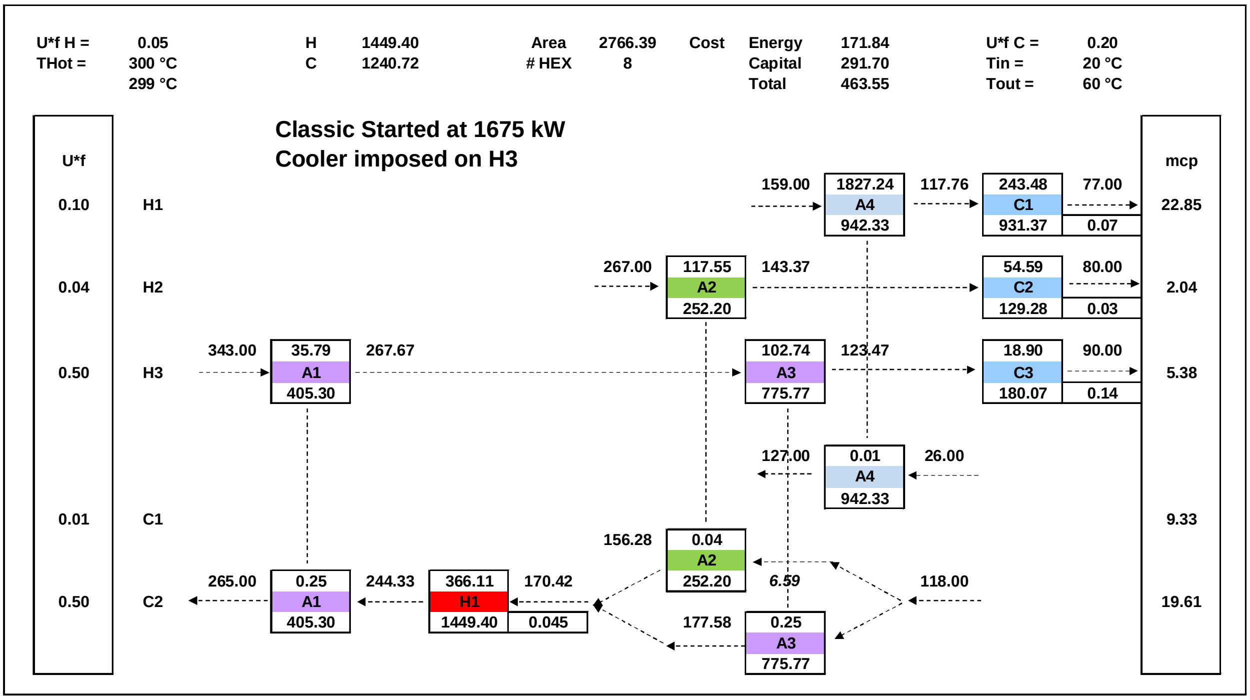

Fig.13.6 ï Result with classic approach ï Starting at 1675 kW Heating ï Cooler imposed