Case 26 - The power of Crisscross optimisation prior to design in heat exchanger network synthesis.

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1. **First example - a data set of 7 streams**.

This example was first studied by Ponce-Ortega et al. in 2008[1], by M-C Aguitoni et al. in 2019 [2] and by Y. Xiao et al. in 2021 [3].

Stream data and financial parameters are given in Table 26.1.

Table 26.1 – Data for first example

Tsupply	Ttarget	Heat	DT-shift *)	U*f	Descript.	mcp
°C	°C	kW	K	kW/K,m²	-	kW/K
230	35	12948	8.0	0.81	H1	66.4
152	152	33020	0.2	1.78	H2	-
108	108	12870	1.6	1.62	H3	-
50	230	8838	0	0.72	C1	49.1
135	135	18413.10	-10.1	1.91	C2	-
118	118	18498.4	-4.8	1.76	C3	-
80	80	16347.9	-0.6	1.84	C4	-
354	354	4906		2.50	Heating	
30	42	1646.6		1.00	Cooling	
*) DT-shift optimised with crisscross for a heating load of 4906 kW						

Financial parameters			
Heating :	100	$/kW,year	
Cooling :	10	$/kW,year	
HEX-unit cost :	379.5*Area$^{0.65}$		$/y

Hot streams H2 and H3 are condensing streams with latent heat; cold streams C2, C3 and C4 are evaporating streams with latent heat. In case of latent heat, supply and target temperatures are the same. For the analysis, a small difference can be used between inlet and outlet temperatures. Once the networks are set up, the correct temperatures can be restored.

To avoid singularities in the calculation of the log mean temperature difference (LMTD), the authors mentioned above used the Chen approximation [4] or averages. Such calculation leads to lower areas. In this study, areas were calculated with correct LMTD formula, except when the difference between hot side and cold side DeltaT's was lower than 0.00001 K, in which case the arithmetic mean value was used. The areas in the published papers were recalculated accordingly.

For the network in [1] an EMAT (exchanger minimum approach temperature) of 5 K was imposed. This restriction was not imposed in the networks in [2] and [3]. To make results comparable, calculations were done, once with an EMAT of 5 K and once without such restriction.

The composite curves are shown in Figure 26.1.

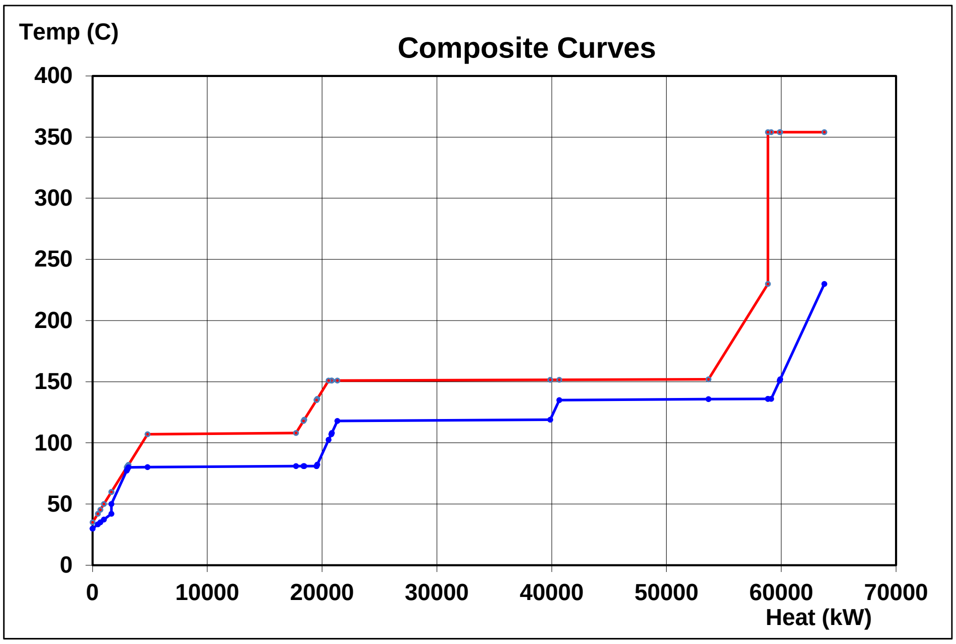

Figure 26.1 – Composite curves

Results of the Pinch Analysis are given in Table 26.2 for a heating load of 4906 kW. The pinch is caused by cold stream C4

Table 26.2 – Results pinch analysis example 1

	Total	Above Pinch	Below Pinch	
HEX area (vertical):	4018.54	2863.4	1155.1	m²
HEX area (criss-cross):	3994.53	2876.9	1117.6	m²
Target # units:	9	7	2	
Cost Utilities :	507.07	490.60	16.47	*000 $/y
Cost Investment :	179.17	132.83	46.34	*000 $/y
Total Cost :	686.24			*000 $/y

The analysis with a DTMin of 5 K indicates a minimum heating of 5106.4 kW. The trade-off curve shows a minimum for a heating load of 4906 kW; this would suggest that, without an EMAT restriction, the cost would be lower. Although differences in heat transfer coefficients are small, Crisscross optimisation suggested differentiated DT-shift values as indicated in Table 1 for a heating load of 4906 kW.

Trade-off curves are shown in Figure 26.2. There are several alternatives: Classic and with Crisscross for 2 systems with segregation at the pinch (Stream 7), one single system leading to 8 heat exchanger units and 2 systems with a split at Stream 1, also leading to 8 units. The areas for all Classic cases are the same for the same heating and so are all areas for all Crisscross cases. The differences are caused by the different number of units and the different distribution of the areas in combination with the specific cost function for the units.

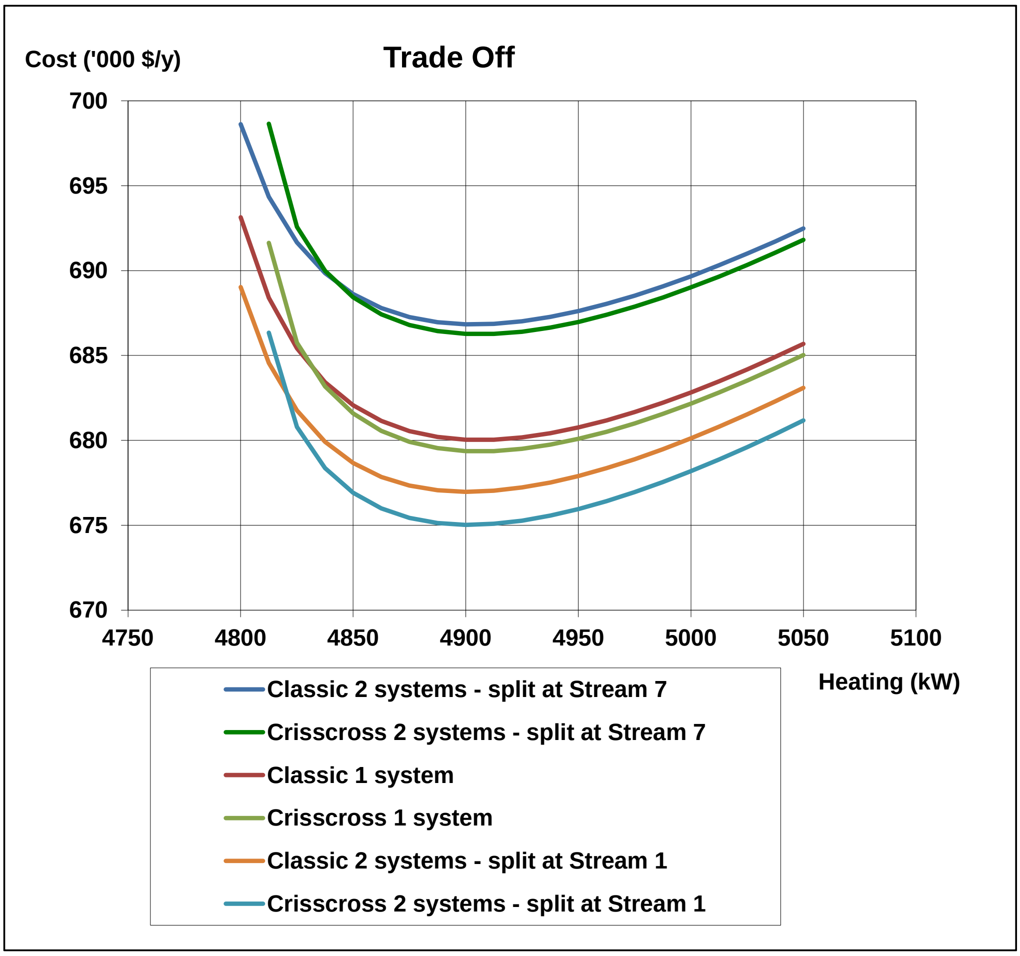

Figure 26.2 – Trade- off total cost versus energy

The grid generated by the analysis has 13 integration bands (superstructures). Application of LP on the grid generates a network with 24 units for an investment cost of 179.20 k$/year. The number of integration bands can be reduced to 10, resulting in a network with 19 units with an area of 3978.83 m^2 costing 178.96 k$/year. The number of units can be further reduced from 19 to 9 by incremental evolution.

The networks from Ponce-Ortega and Aguitoni are shown in Figure 26.3 and Figure 26.4 for an EMAT of 5 K. The optimum network developed in this study is shown in Figure 26.5 and is identical with the network proposed by Xiao et al. If no EMAT is imposed, then the heating drops with 4.1%, the cost with 13.3% to 13.8%. The structure of the networks remains unchanged.

The grid of the Classic analysis shows heaters on both cold streams C1 and C2, the grid of the Crisscross has one heater on C1. The Crisscross analysis generated a grid that enabled synthesis of the optimum network with very simple tools.

Table 26.3 – Results example 1

	Heating	Area	# HEX	# splits	Energy cost	Capital cost	Total cost	EMAT
	kW	m²	-	-	k$/year	k$/year	k$/year	K
EMAT imposed								
Ponce-Ortega et al.	5106.4	3606.22	9	0	529.11	157.20	686.31	5.0
Aguitoni et al.	5107.0	3510.75	10	1	529.18	156.12	685.30	5.0
Xiao / this study	5106.4	3482.45	9	0	529.11	154.29	683.40	5.0
No EMAT imposed								
Ponce-Ortega et al.	4898.2	4086.32	9	0	506.21	170.81	677.02	1.83
Aguitoni et al.	4895.9	3991.96	10	1	505.96	169.65	675.61	1.70
Xiao / this study	4895.2	3961.77	9	0	505.88	167.75	673.63	1.67

Literature.

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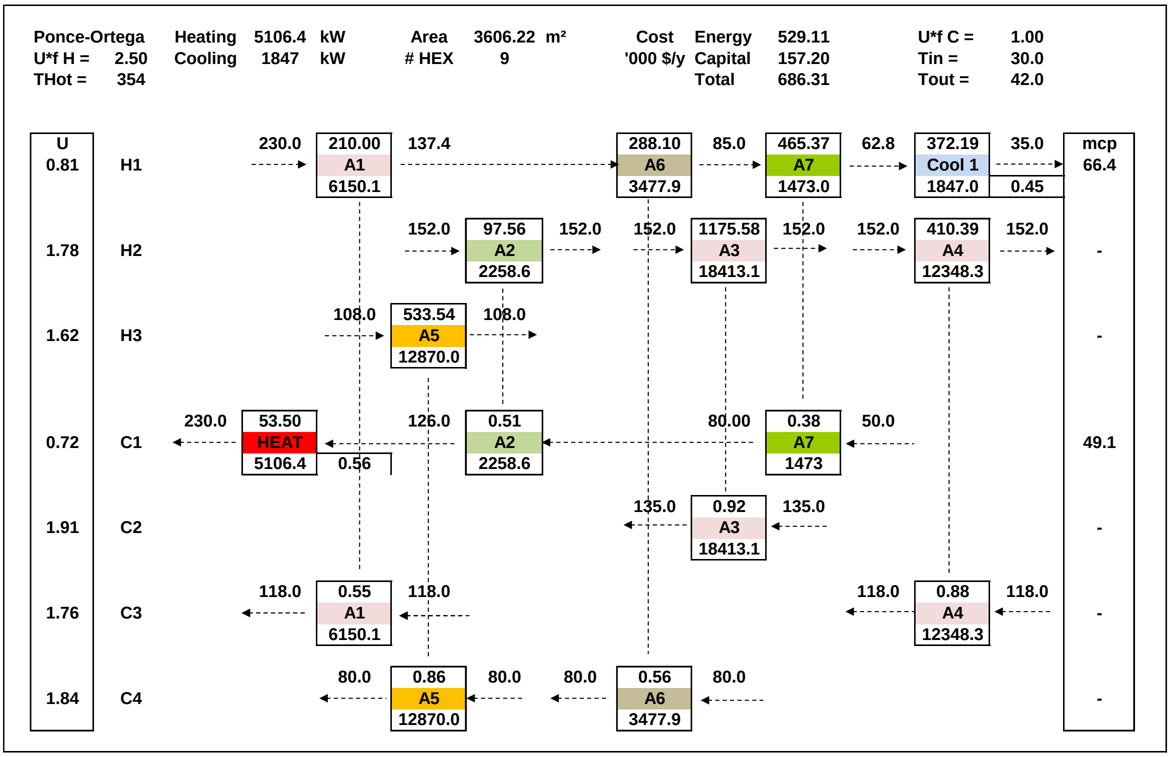

Figure 26.3 – Network Ponce-Ortega et al. example 1

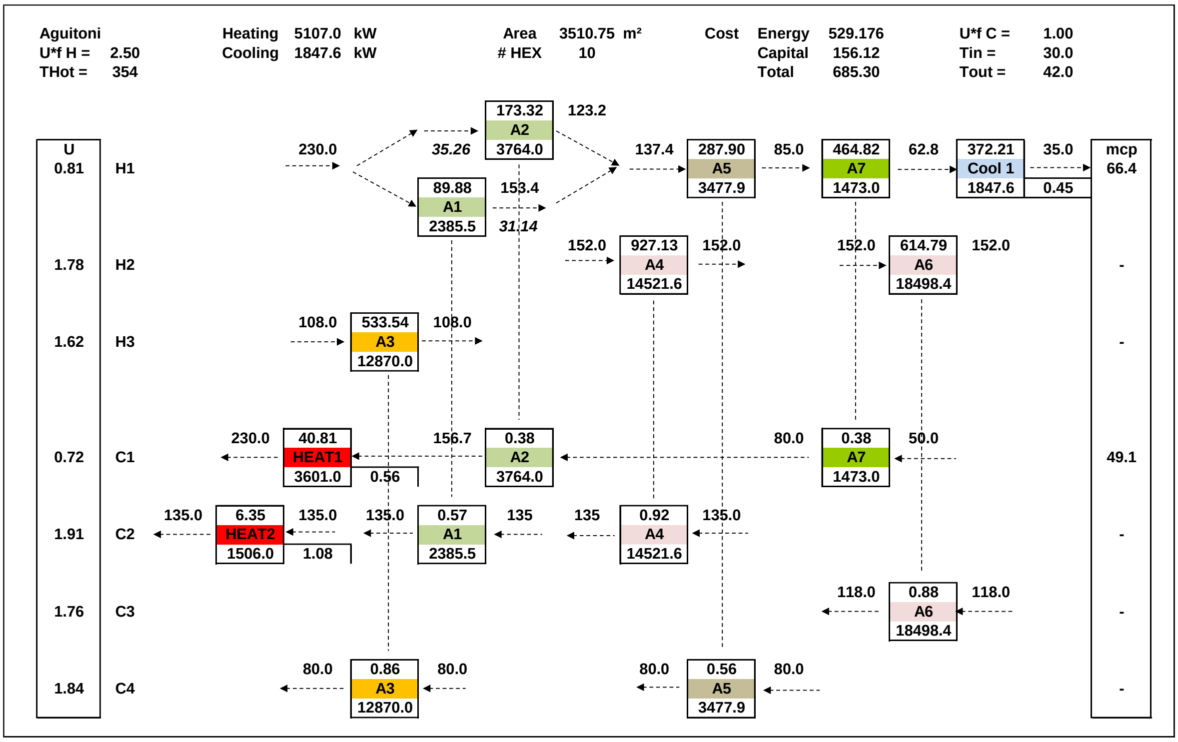

Figure 26.4 – Network Aguitoni et al. example 1

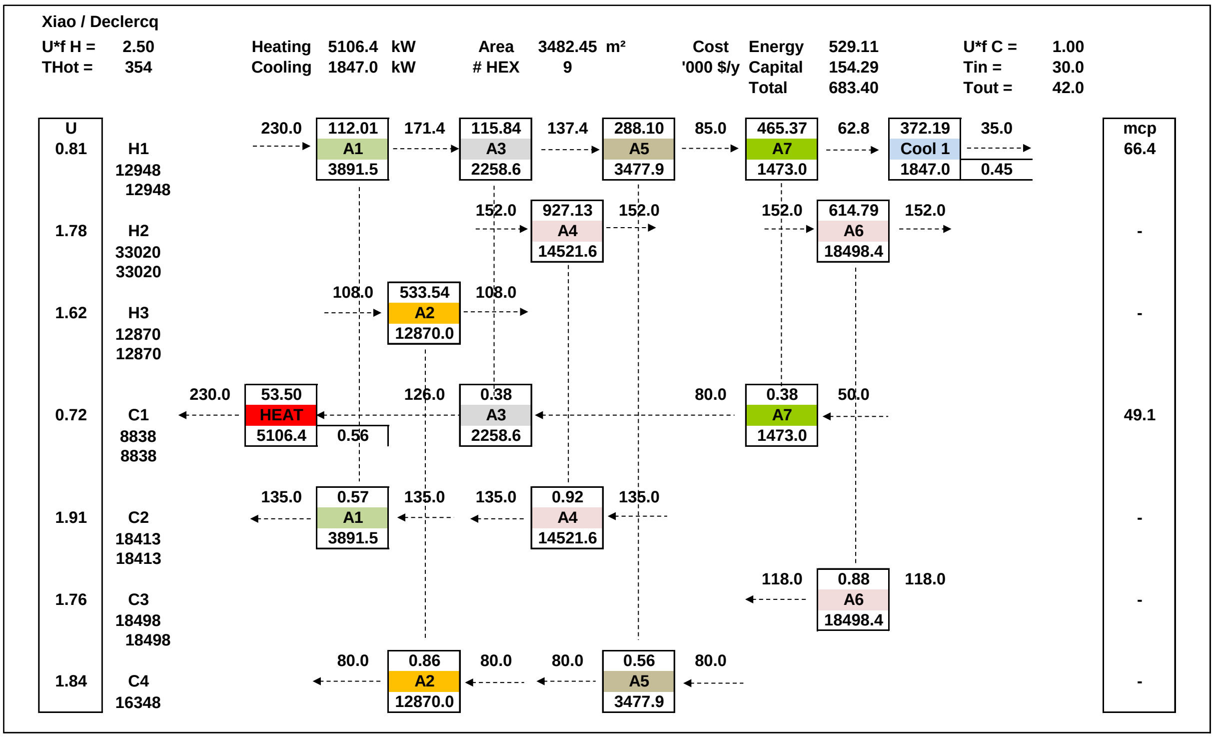

Figure 26.5 – Network Xiao et al. / Declercq example 1

2. Second example - a data set of 20 streams

This example is composed of 13 hot and 7 cold streams plus a hot and a cold utility. Reportedly, the original data set is from Sorsak and Kravanja in 2002 [5], adapted by Escobar and Trierweiler in 2013 [6]. It was further intensively studied by Pavao et al. in 2016 [7] and in 2018 [8], by C Zhang et al. in 2016 [9] and [10], by Xiao et al. in 2017 [11], in 2018 [12] and in 2021 [16], by H Zhang et al. in 2018 [13], by Rathjens et al. in 2019 [15] and by Xu et al. in 2019 [14].

The data set is shown in Table 26.3.

Table 26.3 - Data for example 2

Tsupply	Ttarget	Heat	Optimum shift	U*f	Descript.
°C	°C	kW	K	kW/K,m²	-
576.0	437.0	3211	3	0.06	H1
599.0	399.0	3044	3	0.06	H2
530.0	382.0	2242	3	0.06	H3
449.0	237.0	3129	3	0.06	H4
368.0	177.0	2044	5	0.06	H5
121.0	114.0	1047	-36	1.00	H6
202.0	185.0	4389	-34	1.00	H7
185.0	113.0	603	-37	1.00	H8
140.0	120.0	1198	-36	1.00	H9
69.0	66.0	497	0	1.00	H10
120.0	68.0	454	-36	1.00	H11
67.0	35.0	244	0	1.00	H12
1034.5	576.0	9766	0	0.06	H13
123.0	343.0	2334	49	0.06	C1
20.0	156.0	904	0	1.20	C2
156.0	157.0	3291	-3	2.00	C3
20.0	182.0	4314	0	1.20	C4
182.0	318.0	4242	1	1.20	C5
318.0	320.0	8024	-3	2.00	C6
322.0	923.8	10591	49	0.06	C7
927	927	1831.07	-46	5.00	Heating
9	17			1.00	Cooling

Shift values (DTMin contributions) in Table 26.3 were set with Crisscross optimisation for minimum area.

Composite curves are shown in Figure 26.3 for classic pinch analysis and in Figure 26.4 for analysis with Crisscross optimisation. Available driving force is obviously higher at lower temperatures in the approach with Crisscross. This is further illustrated in the DeltaT versus Q diagram in Figure 26.5.

Trade-off between energy and capital indicates that no cooling is required. Total cost as a function of heating is shown in Figure 26.5 where results both from classic analysis and after Crisscross optimisation are presented. The cost target with Crisscross is 4% lower than the target in the classic approach.

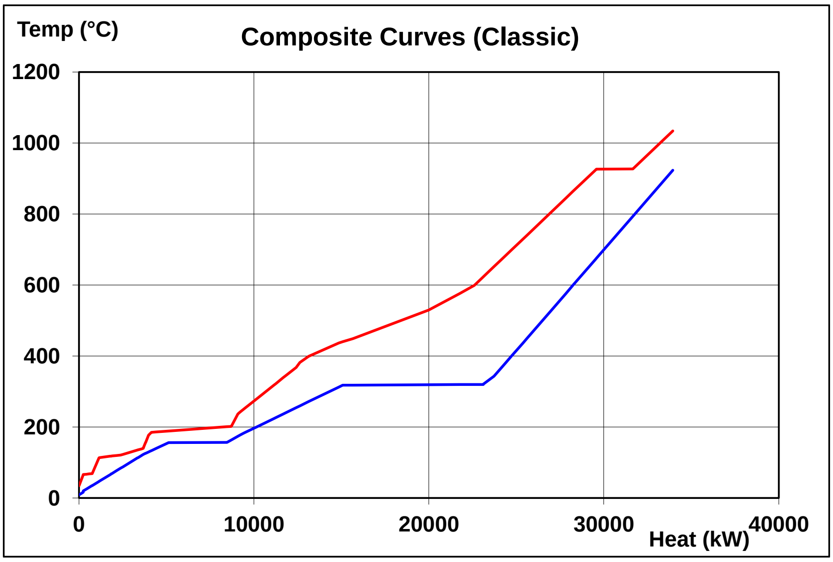

Figure 26.3 – Composite Curves for classic pinch analysis

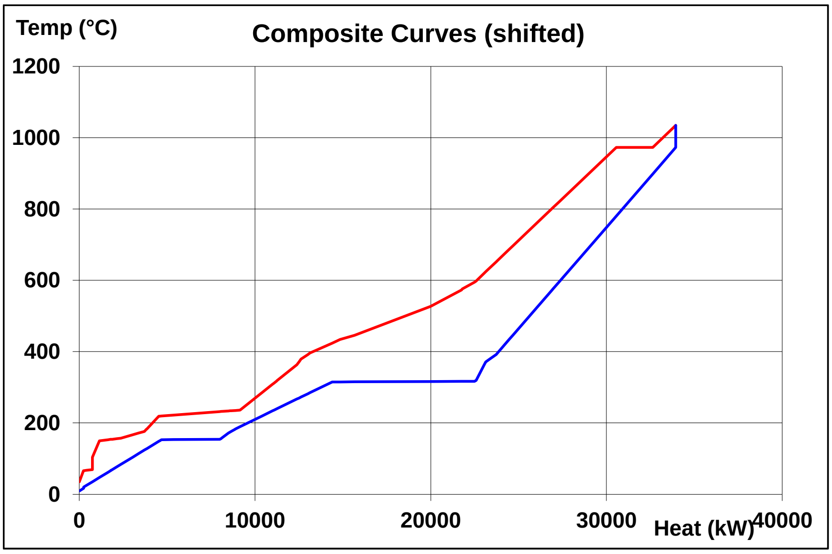

Figure 26.4 – Composite Curves for analysis with Crisscross optimisation

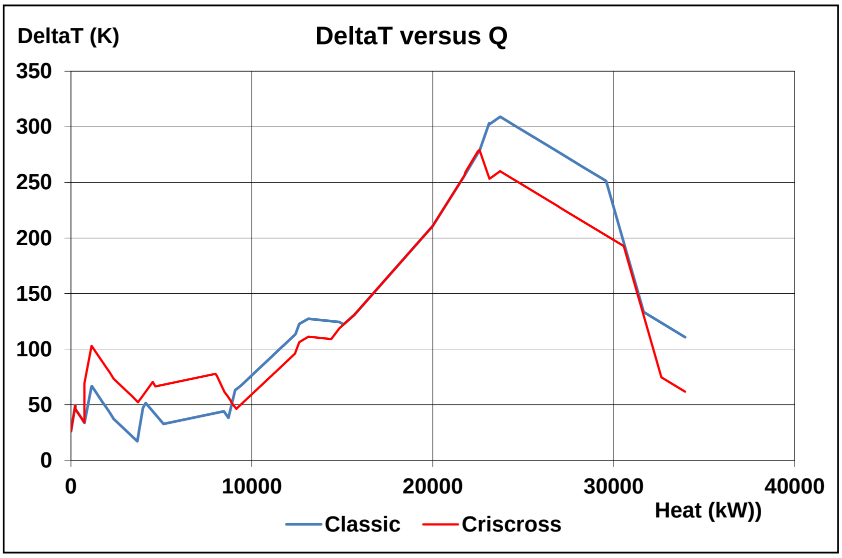

Figure 26.5 – Driving force DeltaT versus Q

Figure 26.6 – Example 2 - Total cost as a function of heating

The design procedure started with generation of the grid with pinch analysis (with crisscross), application of a tick-off procedure, study of potential splits and swaps to eliminate loops. This resulted into the three networks with twenty units and one Heater on cold stream C7 as mentioned in Table 26.4, where they can be compared with the results of other studies. Then a new heuristic rule was applied: "check whether the introduction of an additional utility unit creates a loop through which further optimisation is possible". This rule was applied on cold streams C1, C5 and C6, resulting into three marginally better networks with additional Heaters.

The costs of the best networks are 2.0% lower than the best network published [16]; more than thirty-two networks could be developed with lower cost. The best networks from Table 26.4 with twenty, respectively twenty-one units are shown in Figure 26.7 through Figure 26.12.

Crisscross optimisation prior to design appears to be a powerful tool in view of network synthesis.

Literature.

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Table 26.4 – Results example 2

	Heating	Area	Units	Splits	Cost	Heaters
	kW	m²	#	#	'000 $/year	on stream
Escobar and Trierweiler (2013) [6] *	1938.00	5551.08	21	5	1537.09	C7
Reoptimised by Pavao (2016) [7]	1938.00	5389.05	21	5	1516.48	C7
Developed and optimised (this study)	1938.00	5300.94	20	5	1489.67	C7
Pavao (2018) [8]**	2074.91	5038.59	22	5	1467.80	C1, C4, C7
Bao et al (2018) [17]	2077.51	5053.20	22	3	1462.32	C1, C4, C5, C6
Xiao, Cui, Sun, Chen (2018) [12]	1867.57	5316.06	21	0	1424.17	C1, C4, C5, C6, C7
Hongliang Zhang (2018) [13]	1831.07	5110.00	22	0	1418.98	C1, C5, C6
Xu et al. (2019) [14] ***	1831.07	5295.85	20	0	1412.80	C1, C5, C6
Rathjens (2019) [15]	1831.07	5142.15	20	4	1407.20	C1, C2, C6
Xiao, Kayange et al. (2021) [16] **	1831.07	5025.08	21	0	1396.49	C1, C5, C6
This study	1831.07	4784.32	20	2	1372.97	C7
	1831.07	4784.79	20	1	1373.04	C7
	1831.07	5055.57	20	0	1397.91	C7
	1831.07	4685.85	21	2	1368.99	C1, C7
	1831.07	4784.79	21	1	1369.07	C1, C7
	1831.07	4689.02	21	0	1389.26	C1, C5, C7
* Revised by Pavao (2016) [7]						
** Revised by the author						
*** This network needs no cooler						

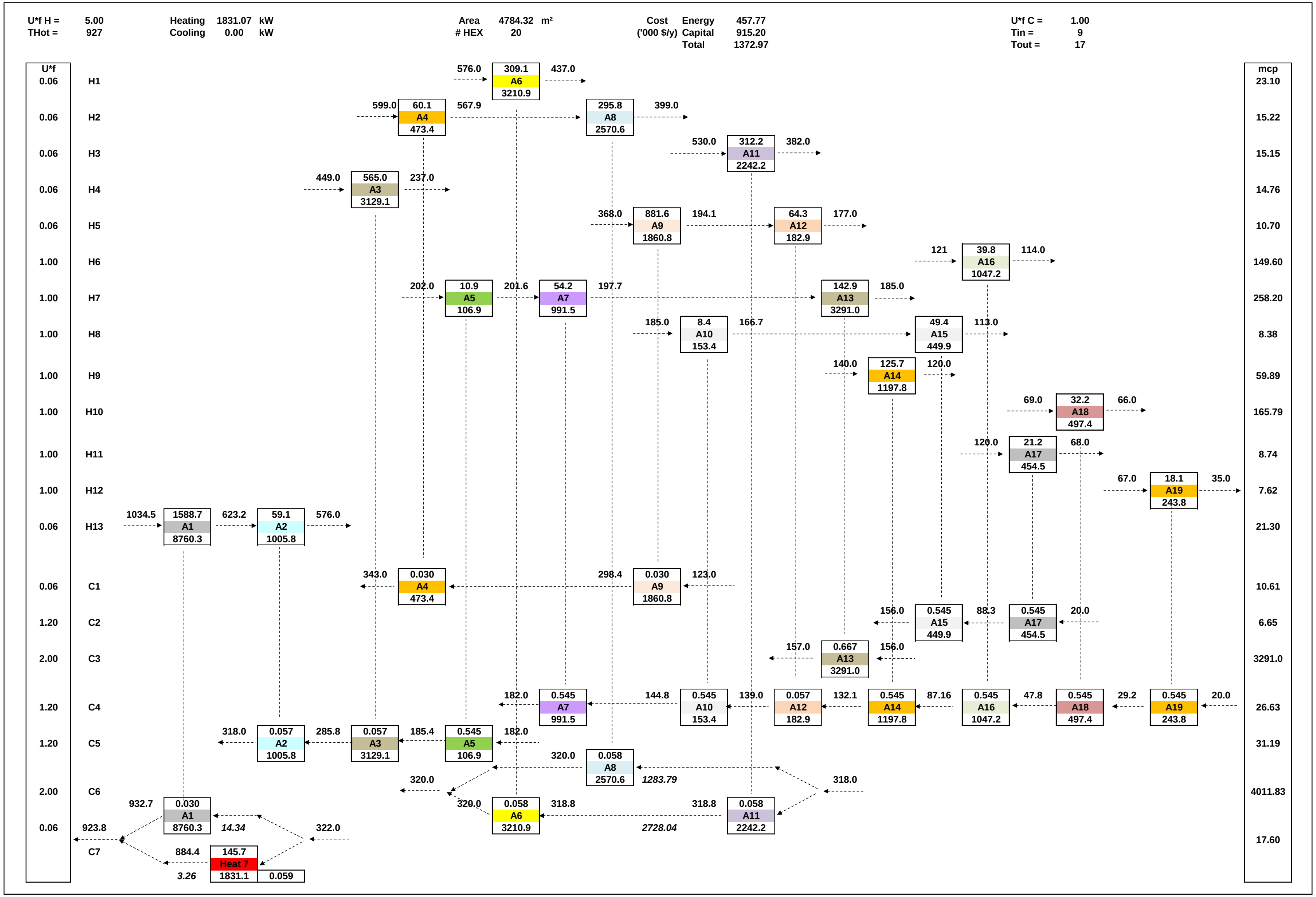

Figure 26.7 - Network with two splits and one Heater

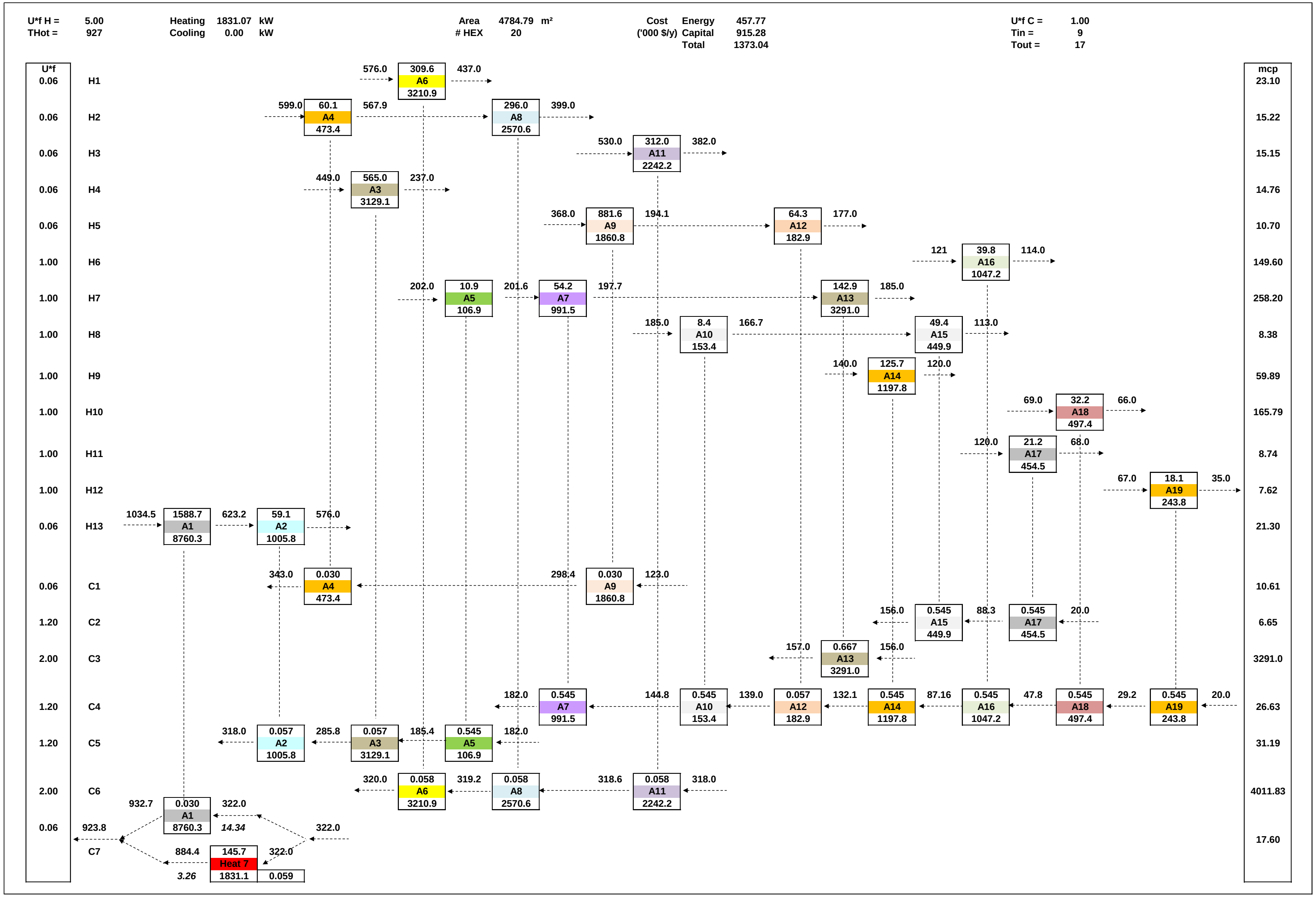

Figure 26.8 - Network with one split and one Heater

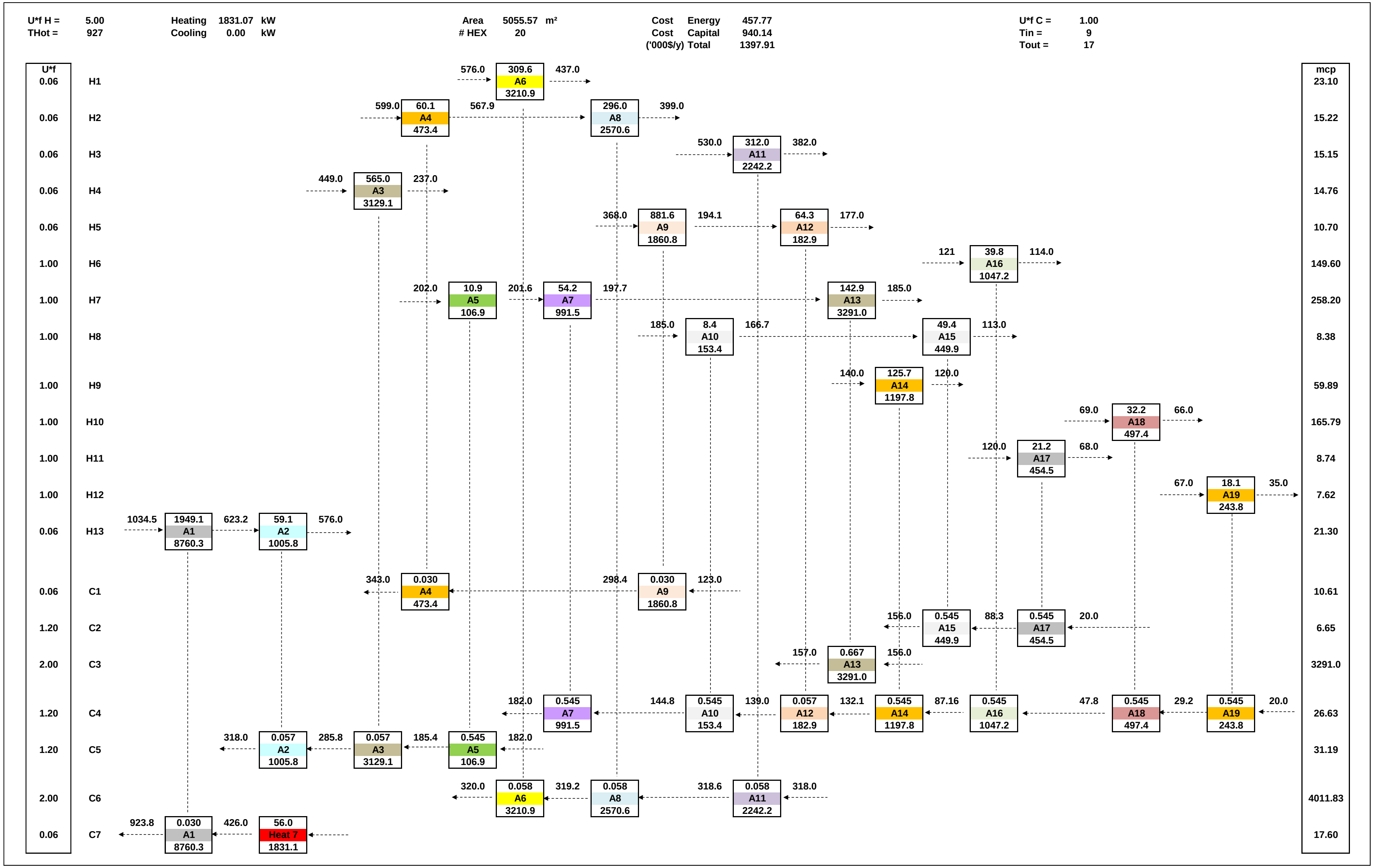

Figure 26.9 - Network without splits and one Heater

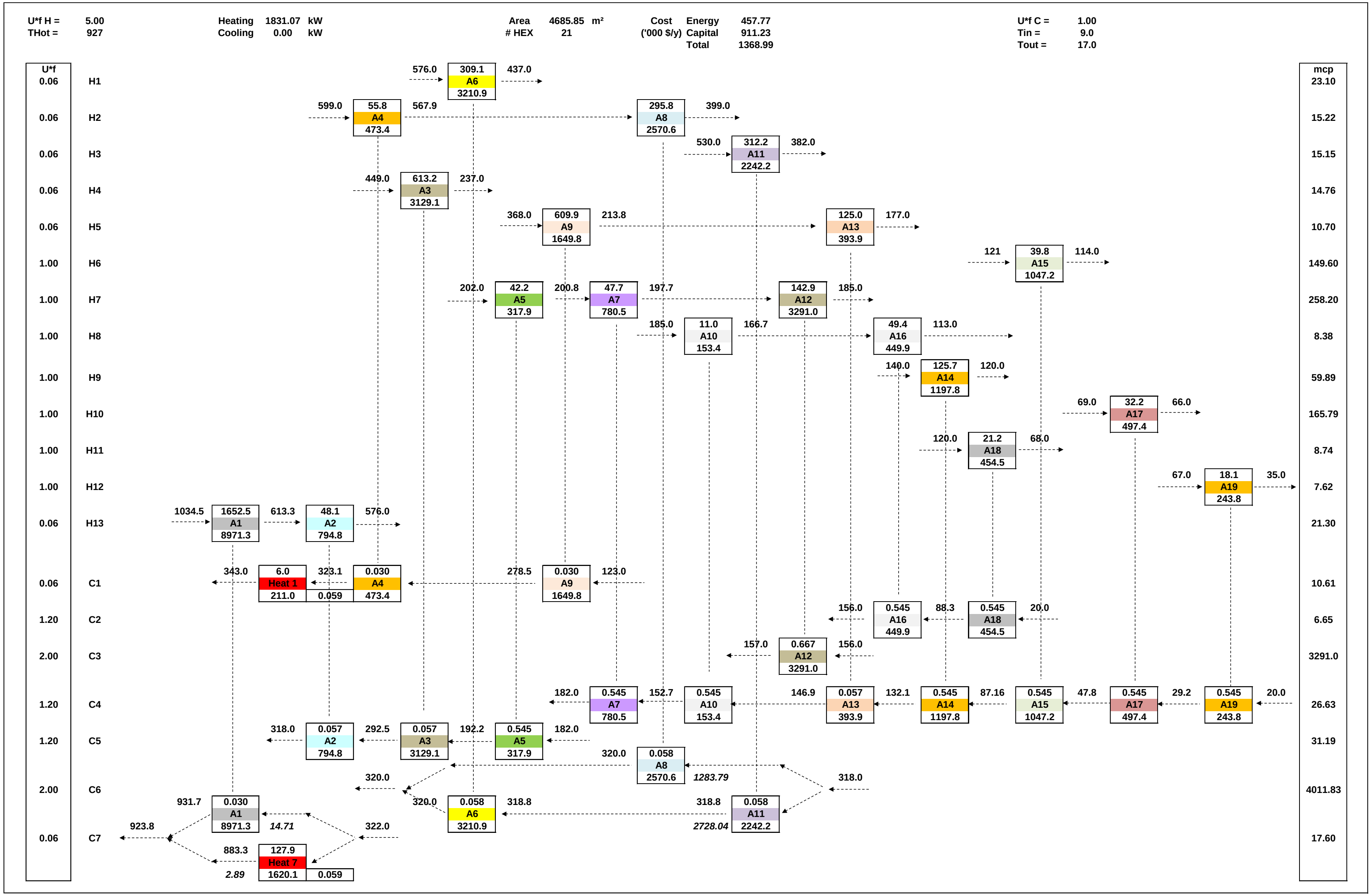

Figure 26.10 - Network with two splits and two Heaters

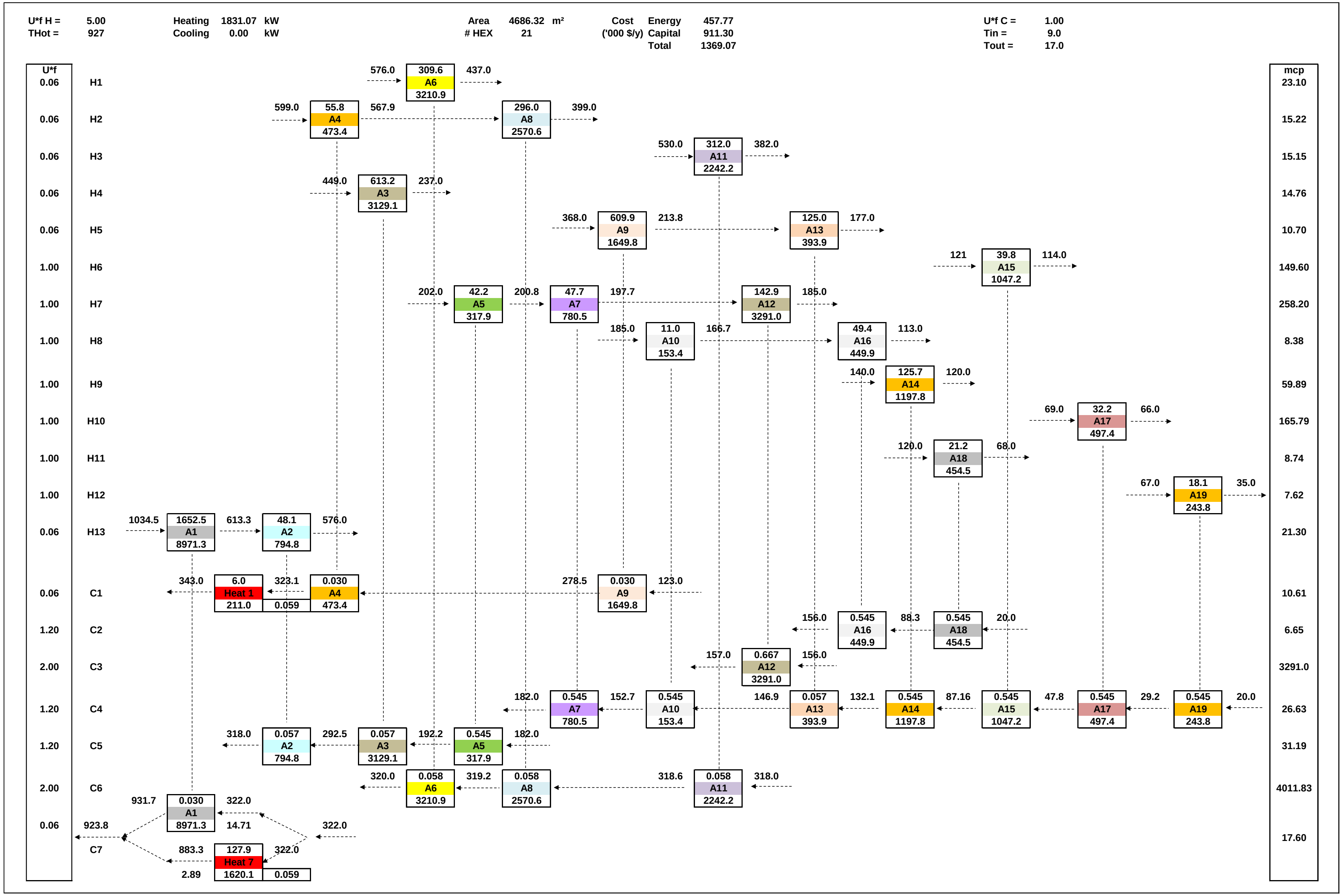

Figure 26.11 - Network with one split and two Heaters

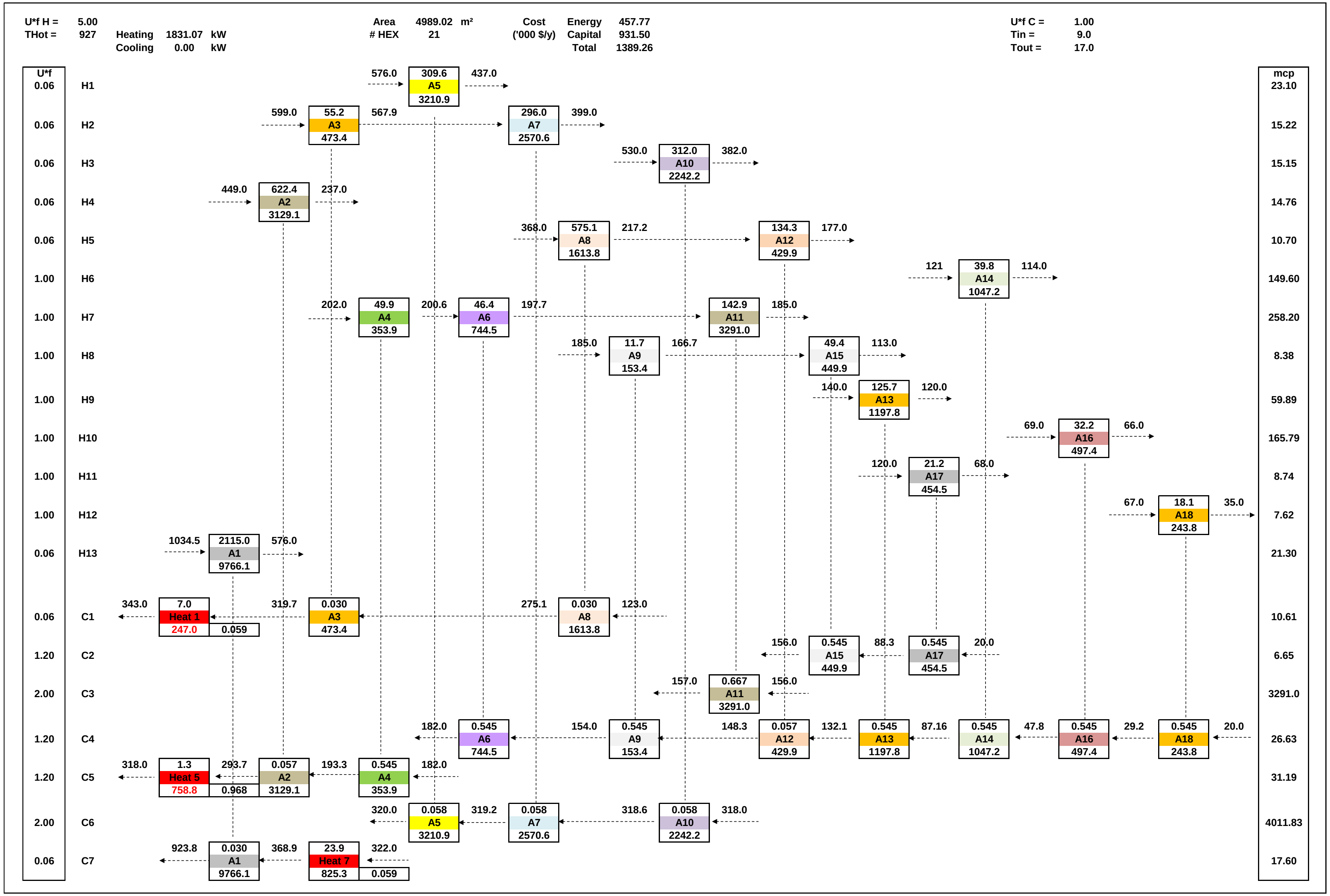

Figure 26.11 - Network without splits and three Heaters