

## The Potential of Pinch Analysis for Network Synthesis.

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### The example of a sugarcane biorefinery by Oliveira.

This example was first studied by C.M. Oliveira et al. in 2017 [1], followed by M-C Aguitoni et al. in 2019 [2] and by Z. Yang et al. in 2022 [3].

The study regards the heat integration of an 1G ethanol and electricity production process in a sugarcane biorefinery. The case was presented as a multiperiod HEN synthesis case, where each of the four periods has a different fraction of bagasse being diverted to the production of 2G ethanol. Only period 1, in which 1G ethanol production is assumed, comprising 8 hot streams and 7 cold streams was considered in these papers.

Stream data and financial parameters are given in Table 1. The heating loads reported in the literature studies are around 100 MW. At the same time, an Exchanger Minimum Approach Temperature (EMAT) of 1 K is put forward. This value is taken as a Heat Recovery Approach Temperature HRAT in Table 1, leading to a heating target of 97370 kW.

**Table 1 - Data for the sugar cane biorefinery**

Tsupply K	Ttarget K	Heat kW	DT-shift K	U*f kW/K,m <sup>2</sup>	Descript. -	mcp kW/K
388.0	306.0	52316	0.5	1.380	H1	638
358.0	357.0	11661	0.5	1.380	H2	11661
355.0	354.0	60307	0.5	1.380	H3	60307
351.0	350.0	24592	0.5	1.380	H4	24592
333.0	332.0	2074	0.5	1.380	H5	2074
385.0	363.0	16434	0.5	1.380	H6	747
421.0	353.0	2244	0.5	1.380	H7	33
351.0	308.0	1849	0.5	1.380	H8	43
321.0	343.0	27632	0.5	1.380	C1	1256
343.0	378.0	45080	0.5	1.380	C2	1288
303.0	362.0	51153	0.5	1.380	C3	867
384.0	385.0	67968	0.5	1.380	C4	67968
381.0	382.0	22466	0.5	1.380	C5	22466
379.0	407.0	9856	0.5	1.380	C6	352
411.0	421.0	3350	0.5	1.380	C7	335
479.0	478.0	97370		2.500	Heating	
298.0	305.0	41342		1.000	Cooling	

Financial parameters	
Heating: 90 \$/kW,year	
Cooling: 50 \$/kW,year	
HEX-unit cost: 4897 + 33 Area <sup>0.78</sup>	\$/year

In the original study [1], investment cost parameters consider heat exchanger cost only, no piping or other installation cost such as instrumentation, control, and engineering. Heat exchanger size was limited to 5500 m<sup>2</sup>.

Streams H2, H3, H4 and H5 are condensing hot streams; streams C4, and C5 are evaporating cold streams. For those steams containing latent heat, a 1K temperature difference has been adopted between supply and target temperatures as is widespread practice in Pinch Analysis. Whilst from technical point of view, the use of a heat transfer coefficient of 1.38 kW/K,m<sup>2</sup> for those streams might be reasonable, using the same low value for all other process streams, however, even if plate heat exchangers were considered, might be less appropriate. Further, fouling has not been considered either. All this might create an unusual relation between energy and capital cost.

Financial results from the analysis with the above data set are shown in Table 2; energy cost is 97.7% of total cost; capital cost is only 2.3%. Even with a Lang factor of 3.0, this ratio would remain extremely low, compared with common industrial practice.

**Table 2 - Analysis results**

	Total	Above	Below Pinch	
HEX area	23 357.2	9 543.6	13 813.6	m <sup>2</sup>
Cost Utilities :	10 699.3	9 600.0	1 099.3	'000 \$/y
Cost Investment :	253.9	112.1	141.9	'000 \$/y
Total Annual Cost :	10 953.2			'000 \$/y

Composite curves are shown in Figure 1. Analysis indicates a pinch caused by hot stream H2 and a near pinch caused by cold stream C5. So, the integration zone between those two streams will show a small driving force as illustrated in the DeltaT/TCold curve in Figure 2. The minimum number of units for a pinched system is nineteen, nine above, respectively ten below the pinch.

Trade-off between energy and capital is shown in Figure 3. The minimum in the curve is at a load of 95.5 MW, for which a driving force at the pinch of less than 0.15 K would be available. Optimisation procedures applied to an initial network would drive into a proposal that is no longer operable in praxis. Hence, it would be appropriate to set a reasonable value for the HRAT when synthesising and optimising the heat exchanger network.

Review of the stream data from a first analysis leads to the following insight:

- cold streams C4 and C7 are not suited for integration and should be heated by hot utility,
- hot streams H5 and H8 are not required for meeting the heating target and can be cooled by cold utility.

So, the number of streams for the synthesis task can therefore be reduced from fifteen to eleven, simplifying such task significantly.

Several analyses were made for heat loads between 102 MW and 98 MW. The resulting grids could be simplified in several ways, and, using LP would lead to different initial networks which, after evolution, resulted into networks with twenty-two and twenty-one units with lower heating loads and lower costs than the best published network so far [3].

Interestingly, the optimisation procedure indicated that the heating could not be further reduced due to EMAT constraints. Since all heat transfer coefficients are the same, there is no reason to differentiate between EMAT and HRAT and, therefore, new analyses were made with the targeted heating of 97370 kW as shown in Table 1.

In case of equal heat transfer coefficients, as is the case here, a different sequence of the process streams at input will generate a different stream grid and initial networks with, potentially, different results after further processing.

First, the stream sequence from Table 1 was used and elaborated in detail. Many networks with twenty-two units were synthesised, three of which satisfying the energy target of 97370 kW and, further, several networks with twenty-one units, two of which were withheld, one satisfying the energy target and one with minimum cost, suffering an energy penalty of only 12 kW. Finally, also networks with twenty, nineteen, eighteen and seventeen units could be developed, no longer satisfying the energy target, however. The best results are mentioned in Table 3 as Series A.

Then, the impact of the stream sequence was tested at random. Hot stream H2 was moved after H4 and cold stream C2 was put after C3. A network with twenty-two units could be developed with a cost of 11713.48 k\$/year. The result is mentioned in Table 3 as Series B. Compared with Series A, no better networks with less units could be developed; networks with nineteen, eighteen and seventeen units were identical in both series.

The heat exchanger networks reported in literature are shown in Figures 4 through 6. The network in [1] was recalculated, giving a marginally higher cost. The network as presented in [2] is not feasible because of a negative DeltaT in the outlet of exchanger A1, caused by an inappropriate steam split. Said stream split was corrected. The network in [3] was recalculated, giving a marginally lower cost.

The networks from Series A are shown in Figures 7 through 15. The network from Series B is shown in Figure 16. An overview of the best results is shown in Table 3, together with the results from literature.

**Table 3 - Results**

	# units	Heating	Area	Cost ('000 \$/y)		
		kW	m <sup>2</sup>	Energy	Capital	Total
Oliveira	19	102 602.4	27 946.9	12 178.55	255.88	12 434.43
Aguitoni	22	102 174.15	25 296.7	12 116.03	263.14	12 379.17
Yang	19	98 849	29 690.6	11 630.55	266.44	11 897.00
This study						
Series A	22	97 370	31 685.9	11 414.62	299.37	11 713.99
	22	97 370	31 685.7	11 414.62	299.48	11 714.10
	22	97 370	31 674.7	11 414.62	299.50	11 714.12
	21	97 370	32 551.0	11 414.62	300.01	11 714.63
	21	97 382	31 921.5	11 416.37	296.47	11 712.84
	20	97 571	32 588.9	11 443.97	293.60	11 737.56
	19	98 052	31 929.0	11 514.19	280.95	11 795.14
	18	99 812	25 900.7	11 771.15	246.61	12 017.76
	17	103 640	19 672.3	12 330.04	209.85	12 539.89
Series B	22	97 370	31 631.2	11 414.62	298.86	11 713.48

The optimization procedure was done with incremental evolution of the heat loads, using steps of 1 kW. This could be further refined to 0.1 kW, however, with an effect on cost of only 1 \$/y. Stream splits had to be calculated with an accuracy of 0.01%. It should be noted that such refinements are not realistic in the real world of process engineering and operation.

Oliveira et al. (quote) used a hybrid stochastic method to solve a single MINLP problem. The hybrid approach was developed by Pavão et al. [4]. It is based on Simulated Annealing (SA) and the so-called Rocket Fireworks Optimization (RFO). SA is used in upper level for combinatorial optimization and RFO is used in lower level for continuous variables optimization. The Rocket Fireworks Optimization combines a modified SA (Continuous Simulated Annealing, CSA) with the Particle Swarm Optimization (PSO) algorithm [5]. CSA is employed to find solutions in a promising region. It is based on random movements (i.e., random quantities are added/removed from continuous variables). The random moves are applied to continuous variables selected by a trivial roulette method. The final CSA solution is maintained and becomes a member of the PSO scheme. With such promising solution included in its initial population, PSO is then able to “refine” that result, finding a better HEN configuration.

Agutoni et al. (quote) applied a hybrid meta-heuristic approach, which combines Simulated Annealing (SA) and Differential Evolution (DE) to solve a mathematical model derived from the superstructure of Yee and Grossman [6] in a bi-level approach. In the upper level, SA is used for proposing new topologies by adding/removing heat exchangers. The encoded topology is sent to the lower-level algorithm (DE). The continuous HEN decision variables associated with the proposed topology (heat loads and hot/cold stream split fractions) are handled by DE aiming for the lowest total annual costs.

Yang et al. (quote) proposed an enhanced stage-wise superstructure (SWS) in which new temperature and heat duty constraints are updated to reduce the redundant combinations and avoid conflicted calculation of non-isothermal mixing energy balances. The model is also extended to allow flexible stream splitting for practical applications. Then, a deterministic-based global solver (GAMS/BARON) is applied.

The present study is based on Pinch Analysis, generating a stream grid that forms the basis for the design task. First, the grid is simplified by combining adjacent integration bands (superstructures) to reduce the number of heat exchanger units. Then Linear Programming (LP) is applied to generate an initial network, which then is further optimized by incremental evolution and optimizing stream splits.

This case demonstrates that no sophisticated software procedures are required to synthesize optimum networks; skilled pinch analysis generates stream grids that offer a perfect basis for setting up an initial network. In this case, the network below the pinch can easily be solved even manually. Because of the near pinch above the pinch, LP is welcome. The resulting initial networks can be further optimized using simple tools such as incremental evolution; merging adjacent integration bands will promote the creation of stream splits and undoing splits might simplify the network whilst reducing the cost. In some cases, swaps of heat loads between streams and introduction of smart splits might offer further cost reduction.

The simplification of the grid by merging adjacent integration bands can be done in different ways, each generating different initial networks. In case of equal heat transfer coefficients, as in the present case, a different sequence of the process streams at input will generate a different initial network with,

potentially, a different result after further optimization. The combination of these two aspects will result in an extremely high number of final networks.

Many published papers mention a rather “ad random” choice of the number of integration bands (superstructures). It should be understood, however, that, for synthesizing optimum networks, said number cannot be chosen arbitrarily, but is defined by the stream grid as produced by pinch analysis.

In this study, only one initial grid was elaborated in detail. More than two dozen networks with twenty-two and twenty-one units were developed with heating loads below 97570 kW and costs below 11740 k\$/y. This demonstrates the potential of pinch analysis.

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Figure 1 -  
Composite curves

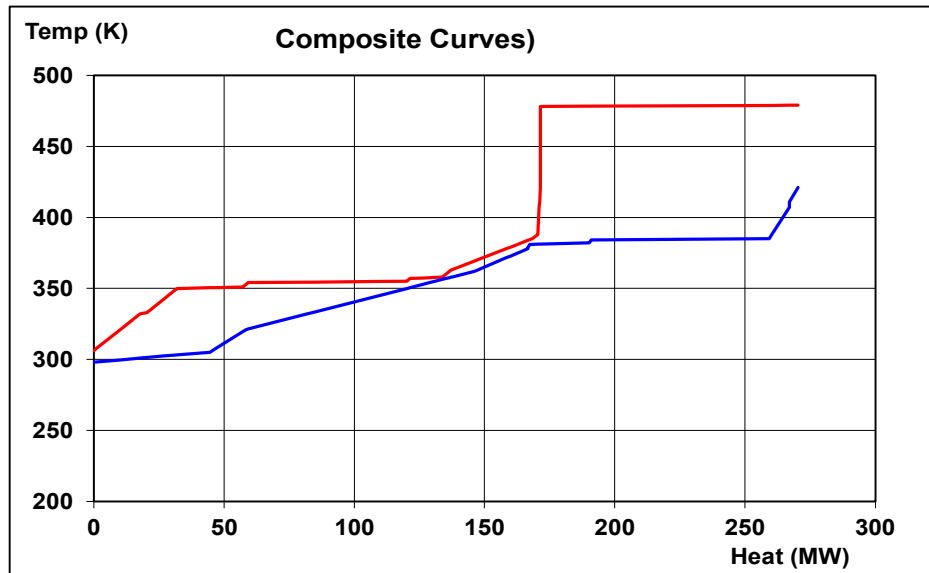


Figure 2 -  
DeltaT/TCold

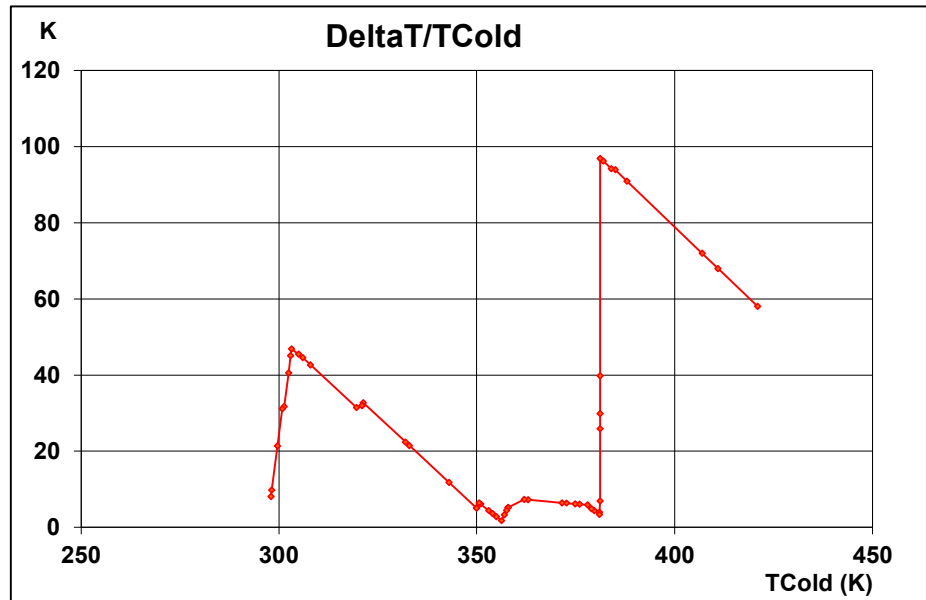
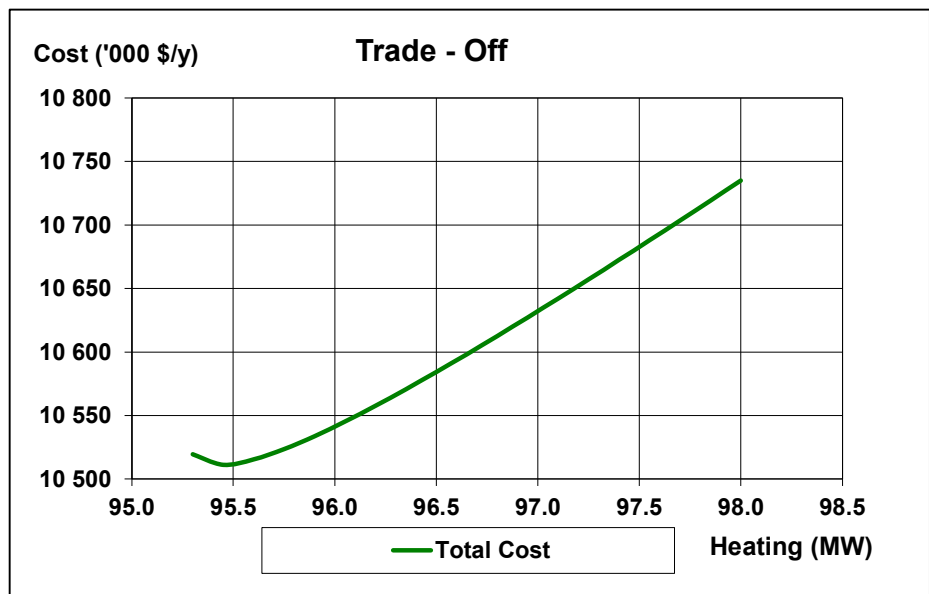


Figure 3 -  
Trade-Off  
Energy vs, Capital



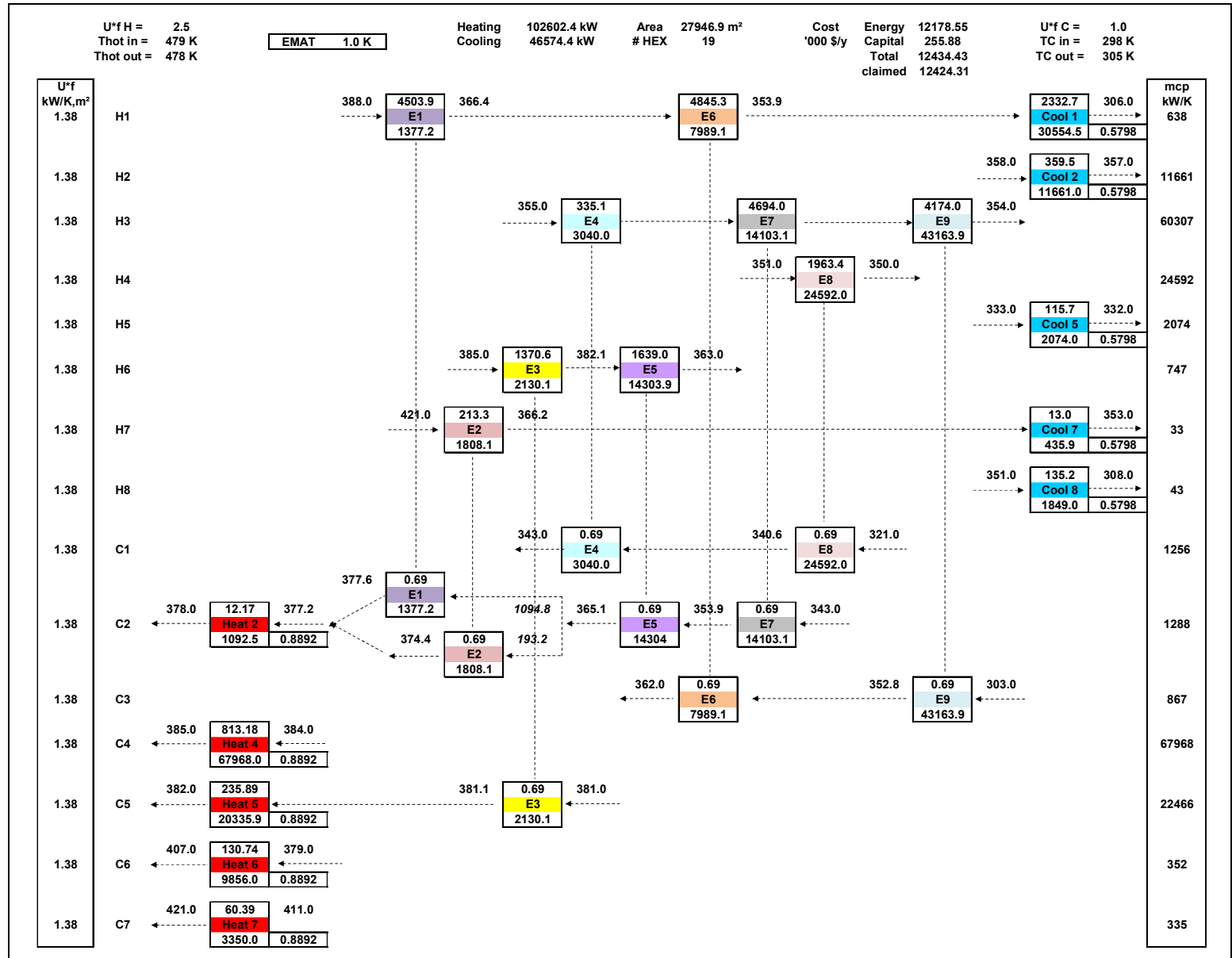


Figure 4 -  
Network by Oliveira

Figure 5 -  
Network by Aguitoni

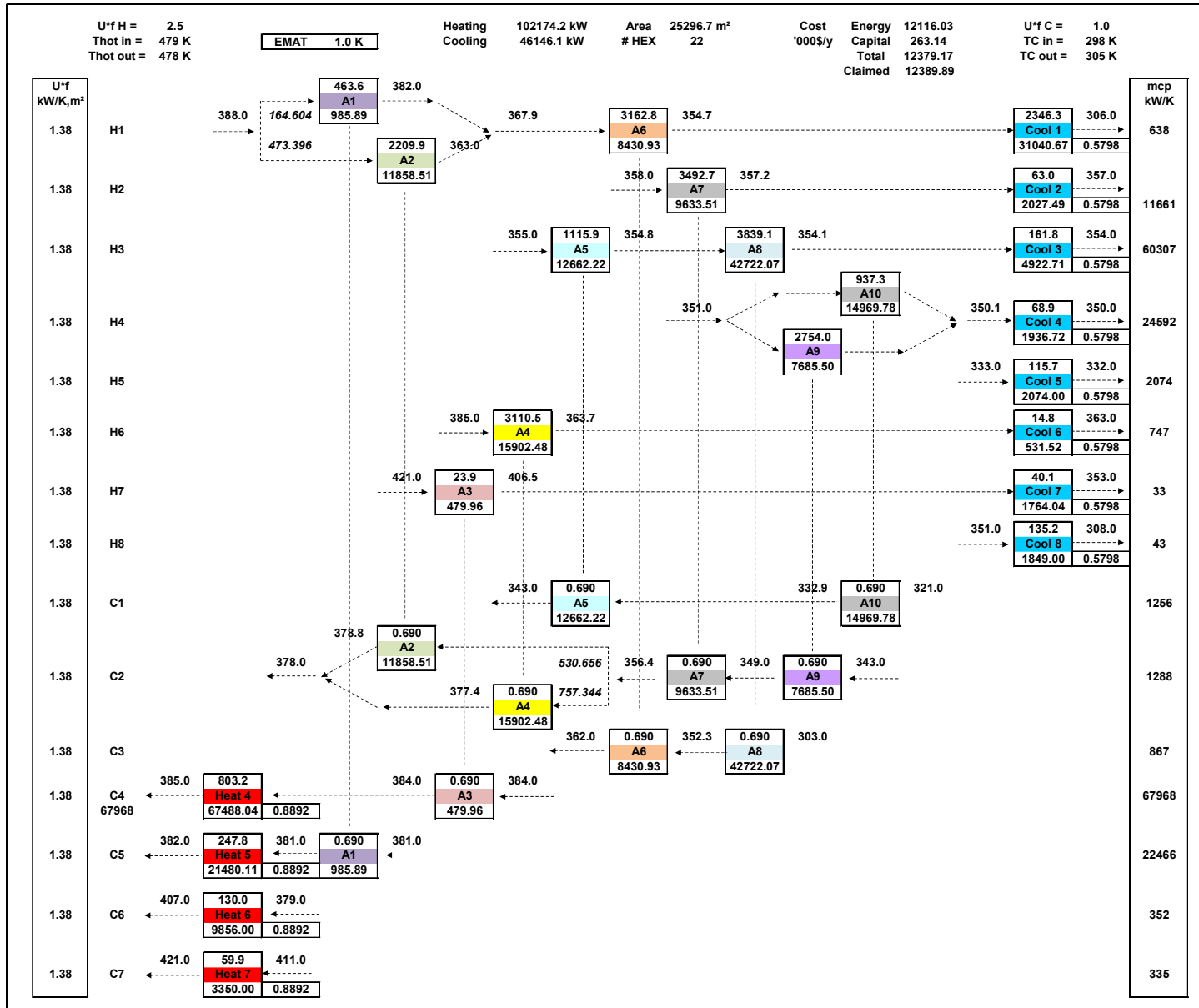


Figure 6 -  
Network by Yang

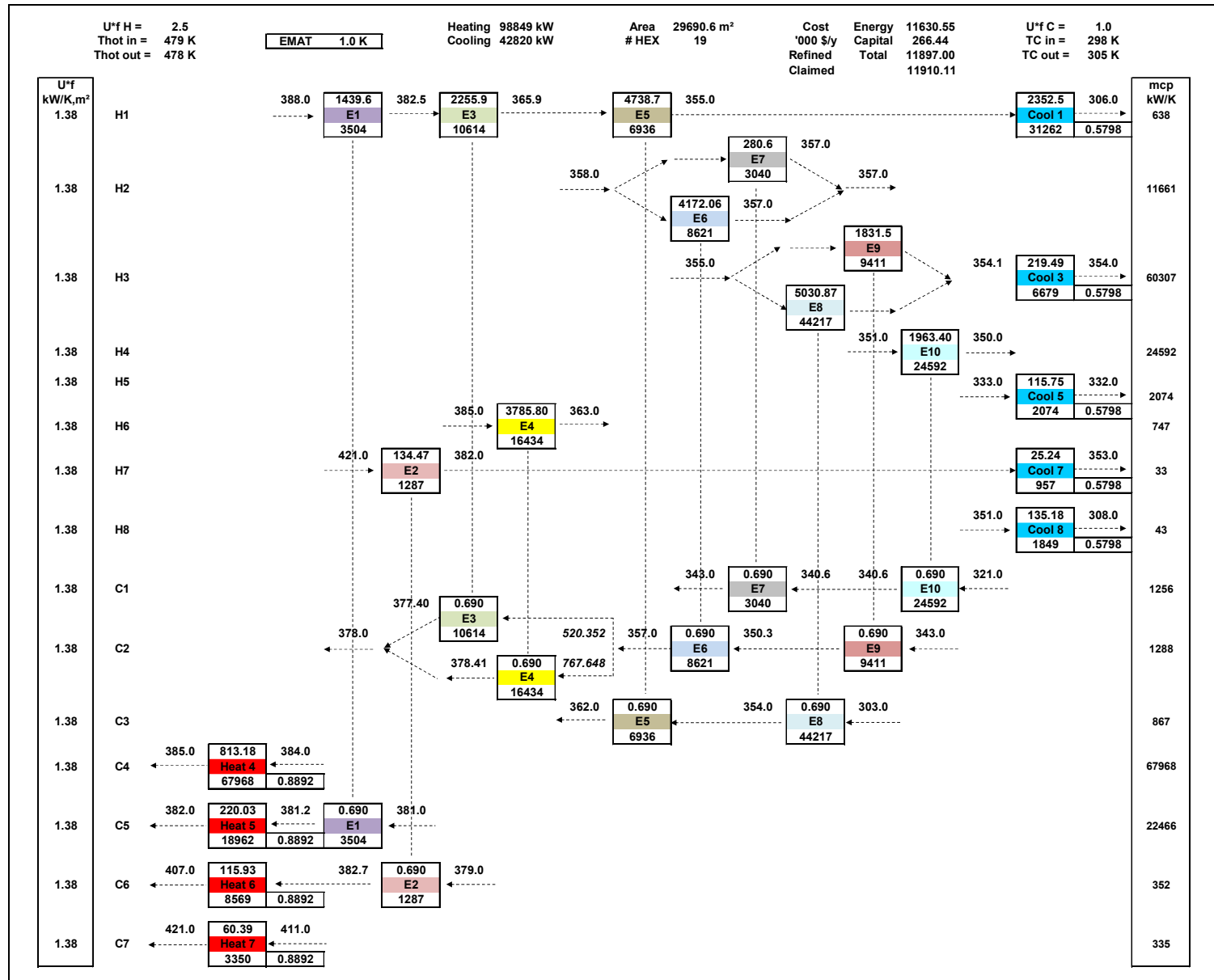


Figure 7 -  
Series A(1)  
22 units -  
E- target

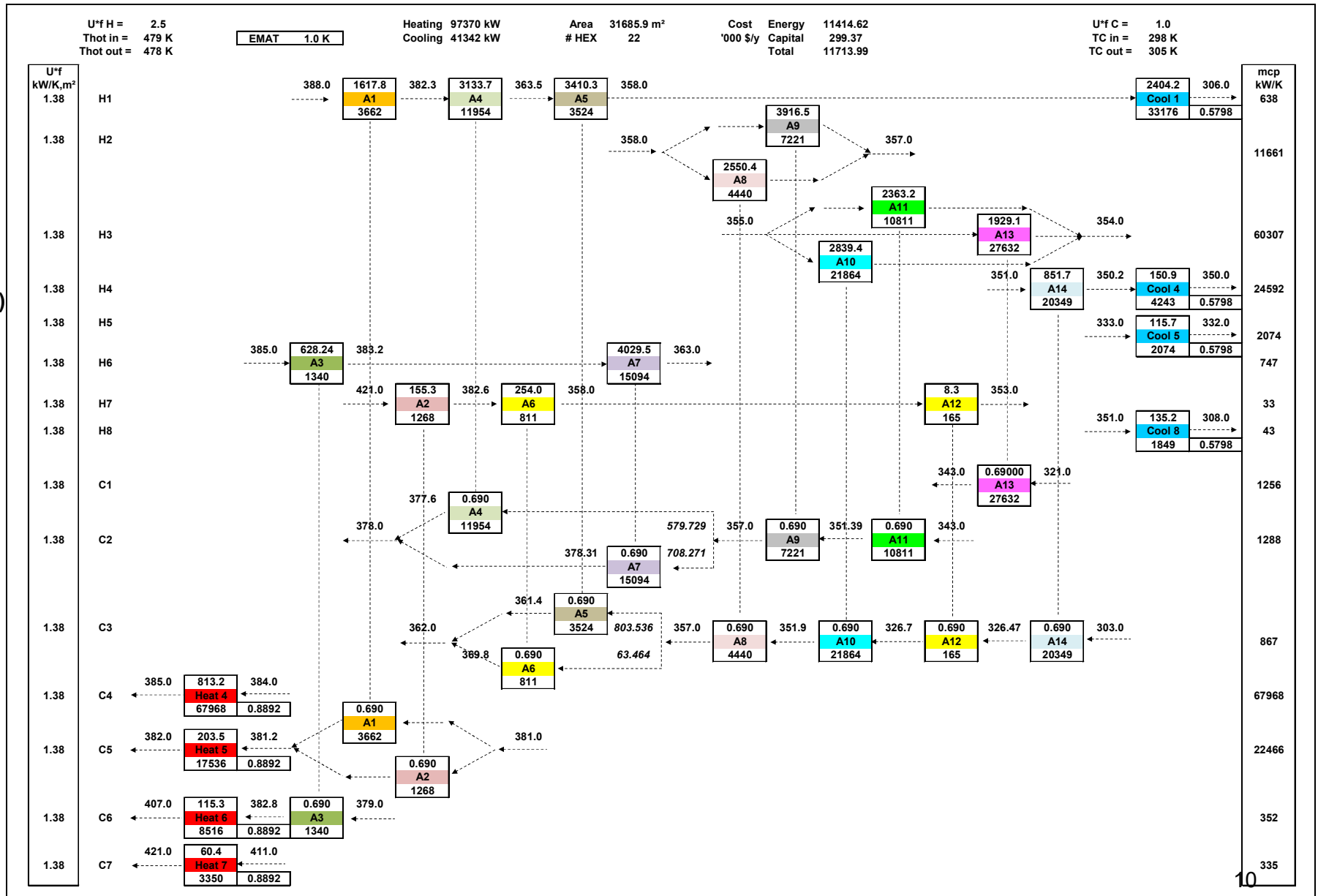


Figure 8 -  
Series A(2)  
22 units -  
E- target

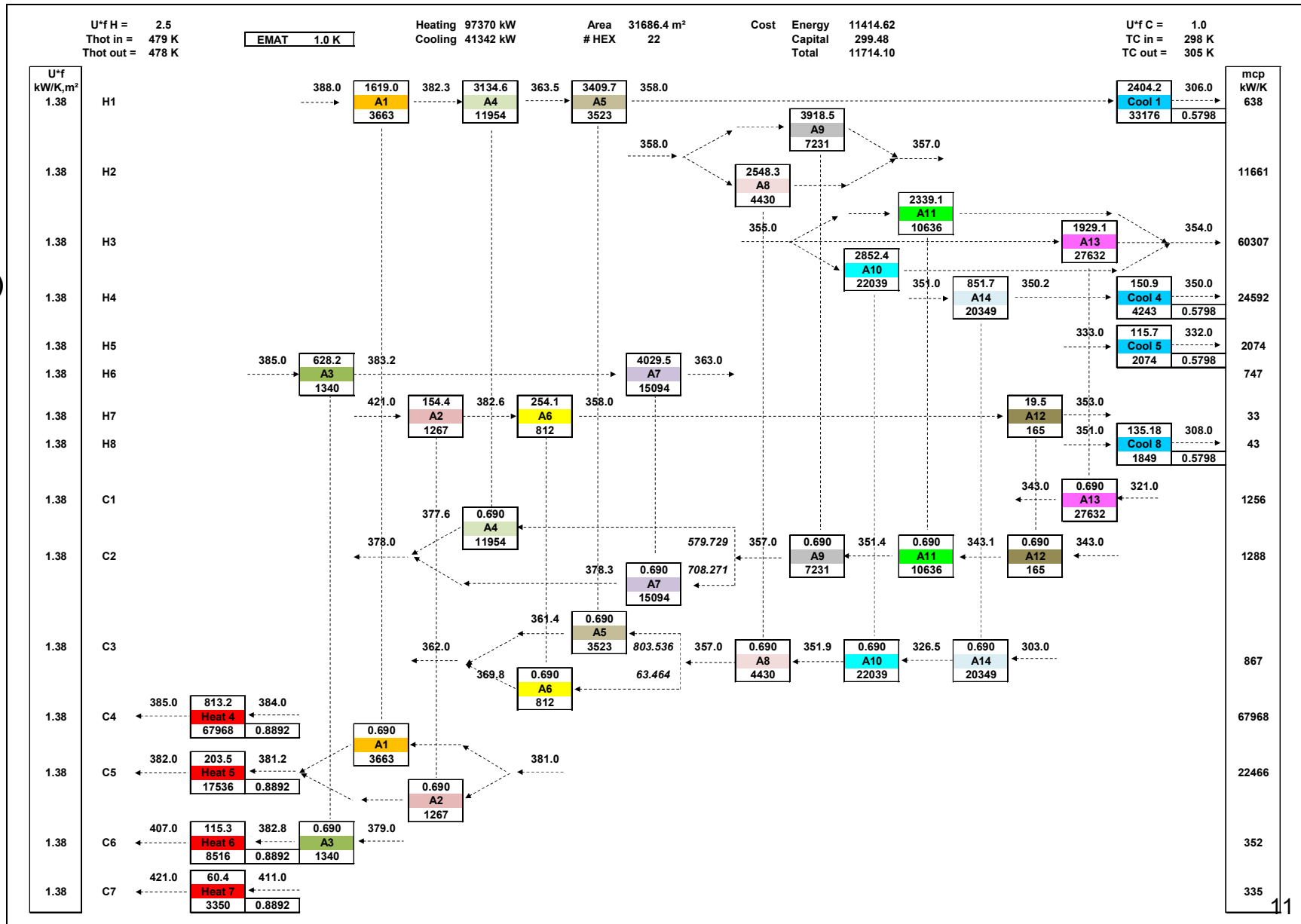


Figure 9 -  
Series A(3)  
22 units -  
E- target

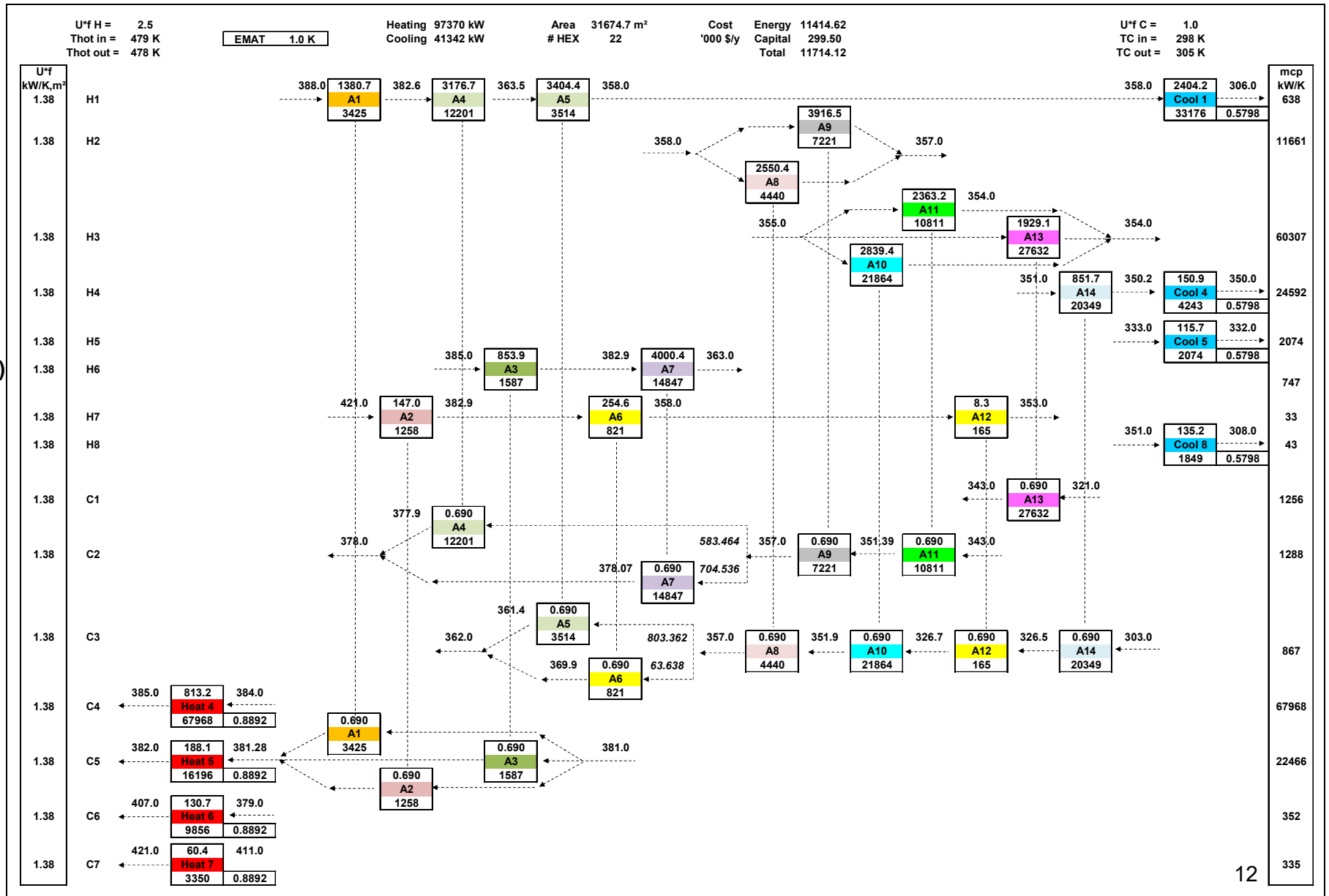




Figure 11 -  
21 units -  
Optimum  
network

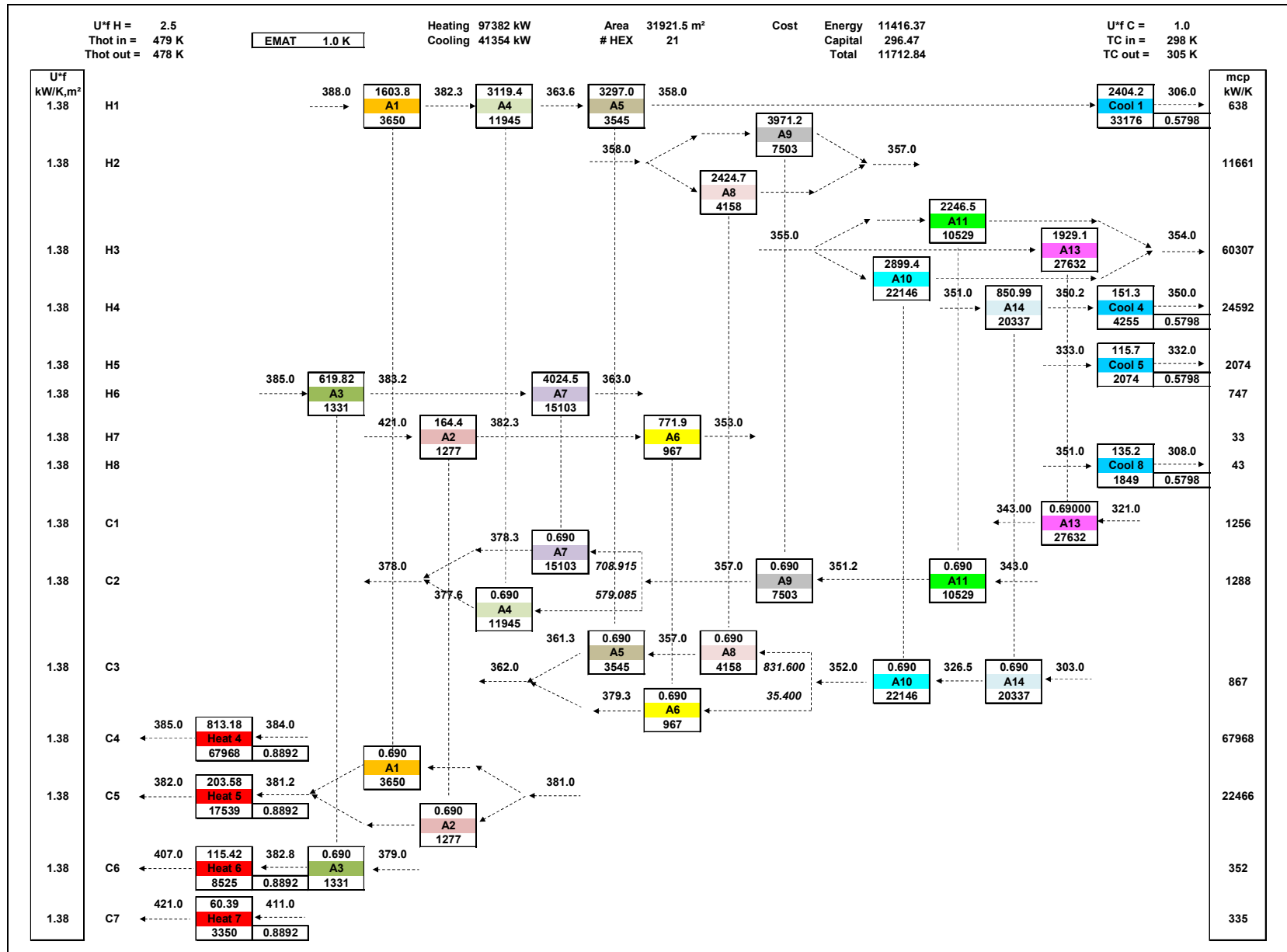
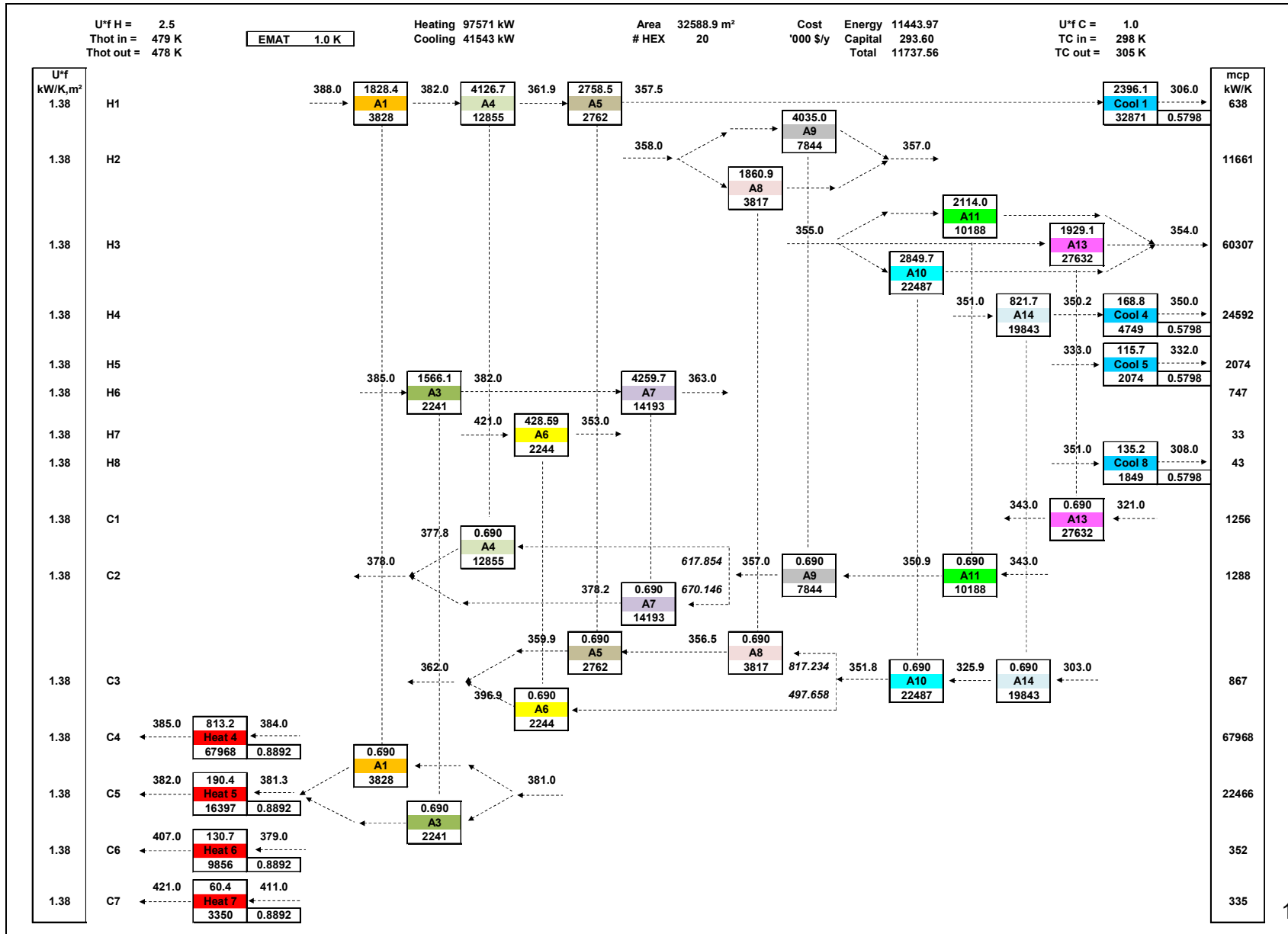


Figure 12 -  
20 units



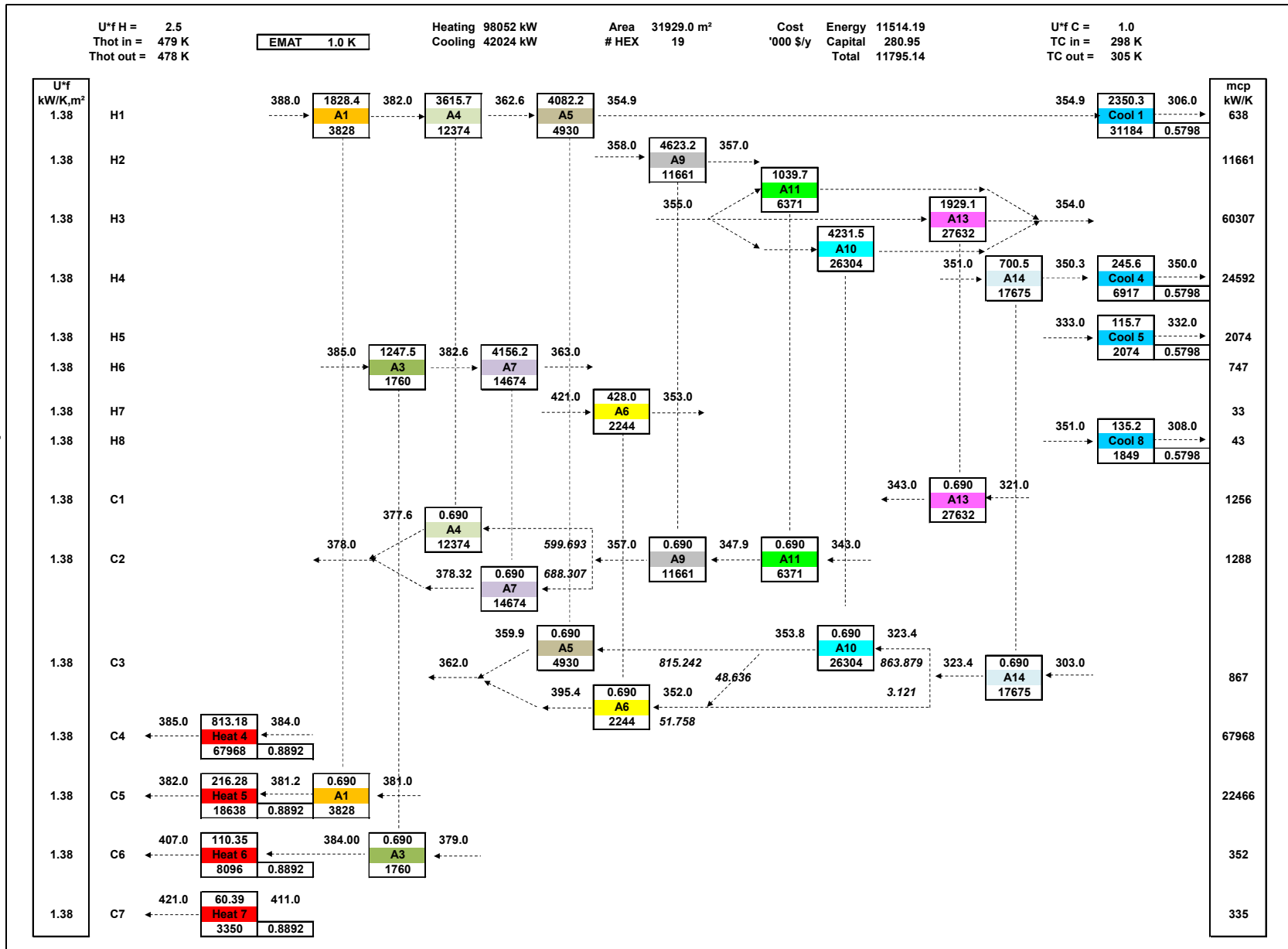


Figure 13 -  
19 units

Figure 14 -  
18 units

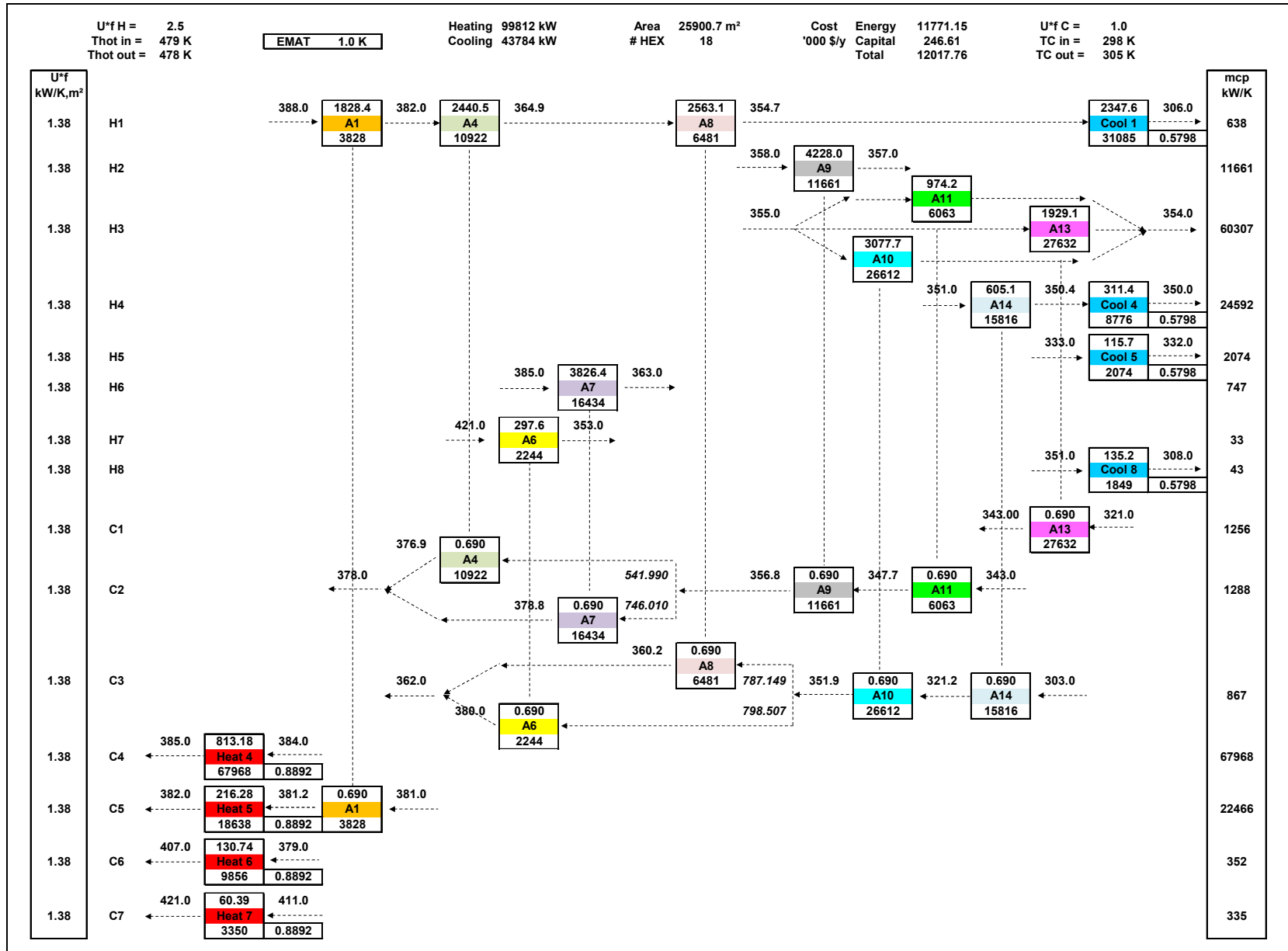


Figure 15 -  
17 units

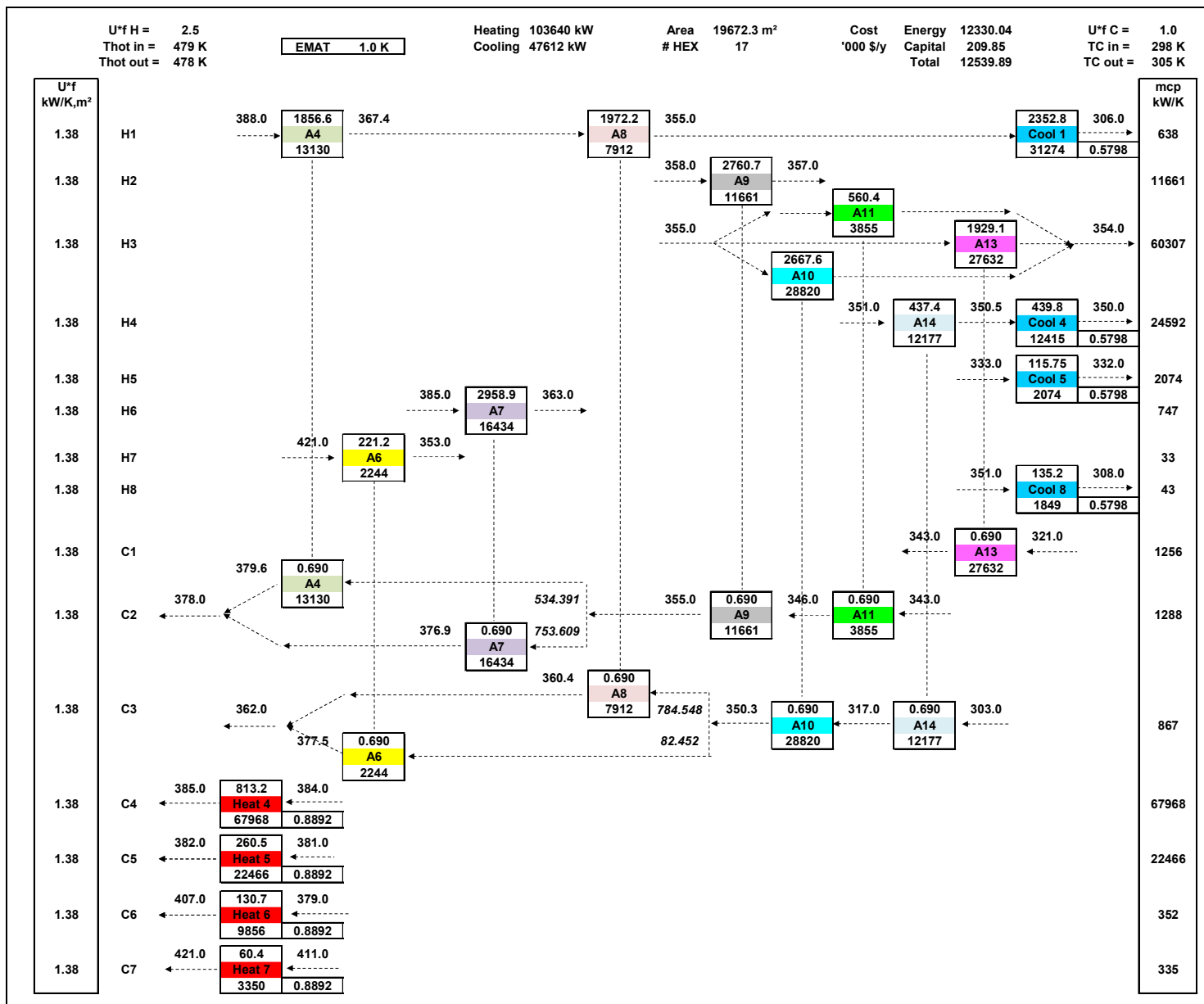


Figure 16-  
Series B  
22 units

