CHAPTER IV
RESULTS AND DISCUSSION

4.1 Example 1

This problem is adapted from Ciric and Floudas (1989). It consists of three hot and two cold process streams and one hot and one cold utility stream. The current design has two coolers and one heater in the process. The stream data is shown in Table 4.1. The existing exchanger network configuration is shown in Figure 4.1. The existing network does not have splitting. This case disallows heat exchanger relocation, but alterations in the HEN may only include new exchanger and area addition or reduction to existing exchangers, as well as the introduction of stream splitting. Since it is desirable to reduce the use of utilities, no additional utility exchangers are considered. The original HEN consumes 17,759 kW of hot utility at \$0.0113/MJ and 15,510 kW of cold utility at \$0.00238/MJ. The life time used for annualized costs and net present value calculations is 5 years, the interest rate is 10%.The allowed amount of area addition are 20% of the corresponding existing area; the allowed amount of area reduction is 50% of the existing area; the maximum area per shell is 5,000 (m^2); the maximum number of shells per exchanger is 4. The minimum allowable EMAT is 10°C. Finally, assuming 350 working days in a year, the annualized cost (\$/year) per 1 MJ/hr utility consumed is 26.4 for hot utility and 5.55 for cold utility. Table 4.2 identifies the existing heat exchangers' original areas, which were calculated using the log mean temperature difference.

Table 4.1 Stream properties for Example 1 (Ciric and Floudas, 1989)

Stream	F kg/s	Cp kJ/kg.C	Tin °C	Tout °C	H kW/m^2.°C
H1	228.5	1	159	77	0.4
H2	20.4	1	267	88	0.3
H3	53.8	1	343	90	0.25
HU (hot utility)		1	500	499	0.53
C1	93.3	1	26	127	0.15
C2	196.1	1	118	265	0.5
CU (cold utility)		1	20	40	0.53

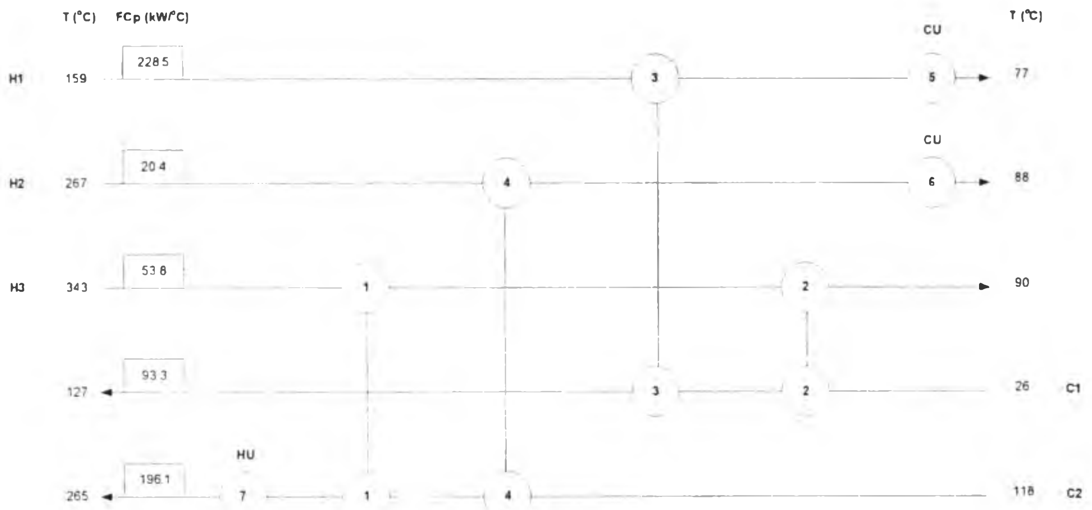


Figure 4.1 Original heat exchanger network for Example 1.

Table 4.2 Existing heat exchanger areas for Example 1

Exchanger	Existing Area (m^2)
1	609.7
2	579.2
3	1,008.5
4	117.96
5	787.5
6	104.6
7	246.75

The cost relations for area adjustment for Example 1 are taken from the paper by Barbaro et al. (2005) and are shown Equation 4.1, 4.2, 4.3 and 4.4. A cost is assigned to splitting of $10,000.

$$\text{Heat exchanger cost (\$)} = 17{,}300 + [857\times\text{Area (m}^2)] \tag{4.1}$$

$$\text{Area addition cost (\$)} = 8{,}650 + [857\times\text{Area}_{\text{added}}(\text{m}^2)] \tag{4.2}$$

$$\text{Area reduction cost (\$)} = 8{,}650 + [5\times\text{Area}_{\text{reduced}}\ (\text{m}^2)] \tag{4.3}$$

$$\text{New shell} = 17{,}300 + [857\times\text{Area}_{\text{shell}}\ (\text{m}^2)] \tag{4.4}$$

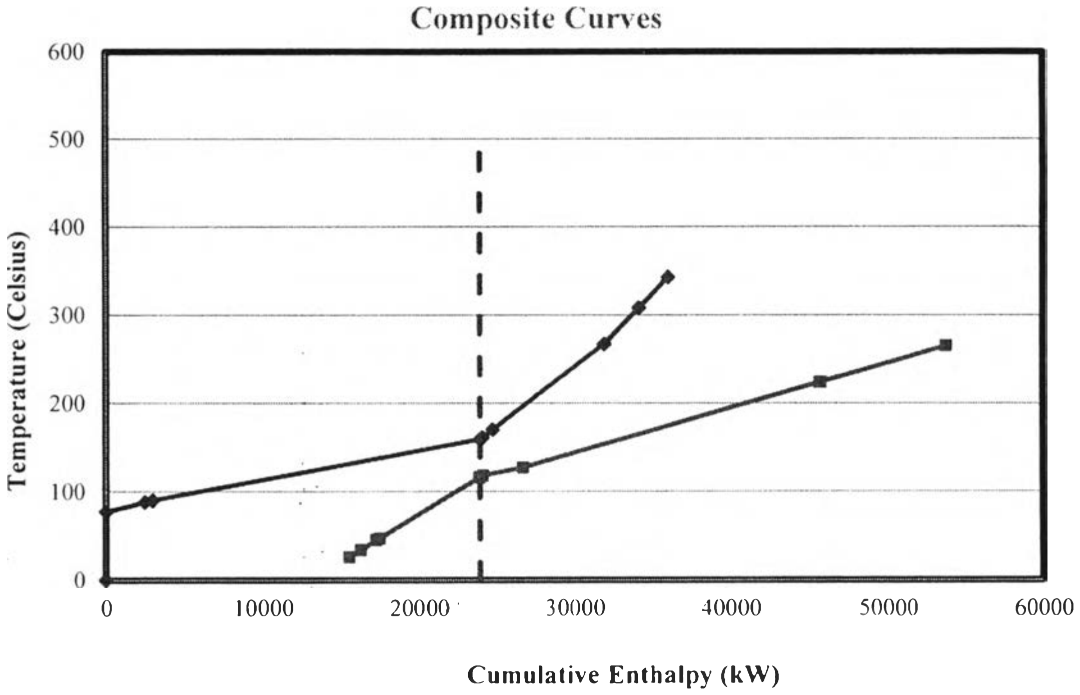


Figure 4.2 Composite curves of the existing network.

4.1.1 Discussion

In this section, the results for the retrofitted design of the process pinch and the MILP are compared. Each method was applied to the same HEN retrofit problem using the same constraints and cost functions. Furthermore, we will only discuss the results of disallowing the relocation of existing heat exchangers. This scenario allows manipulating the area of existing exchangers as well as adding new exchangers and introducing stream splitting.

4.1.1.1 Process Pinch Results

The ΔT_{min} maximizing the ideal NPV was determined from the graph below. It shows the maximum NPV of $584,748.3 occurs at a ΔT_{min} of 25.2 °C with hot and cold utility savings of 4,133 kW.

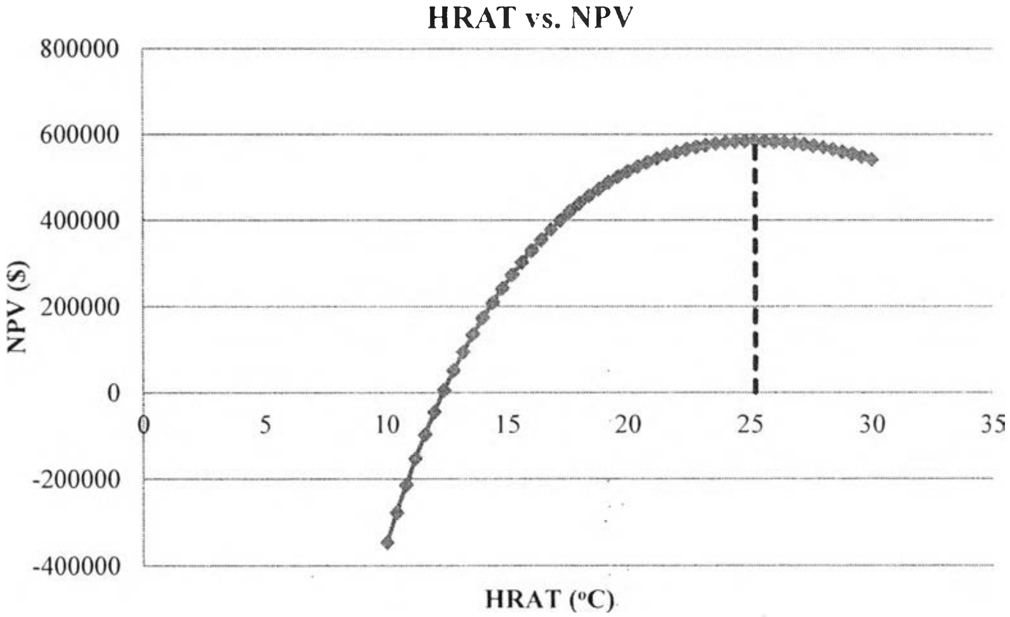


Figure 4.3 HRAT versus NPV.

Now that the optimum ΔT_{min} value has been determined, the next step is to generate the stream matches for heat exchange in the new network. To do this, a grid diagram of the process is analyzed with the pinch temperature represented as two vertical lines at the middle of the grid. For this section, Example 1 will be used to demonstrate how to match streams to exchangers. The grid diagram for the retrofitted network of Example 1 is illustrated in Figure 4.5.

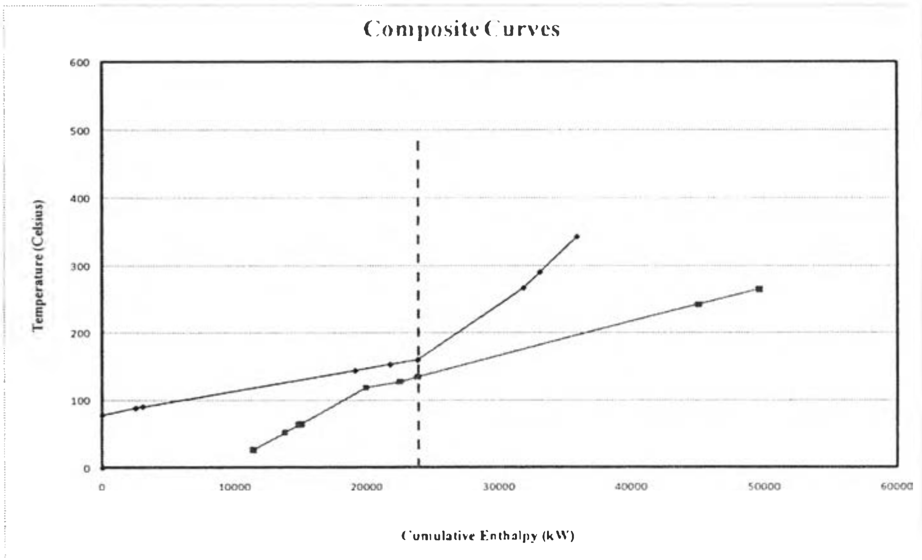


Figure 4.4 Composite curves of HEN retrofit at ΔT_{min}=25.2°C.

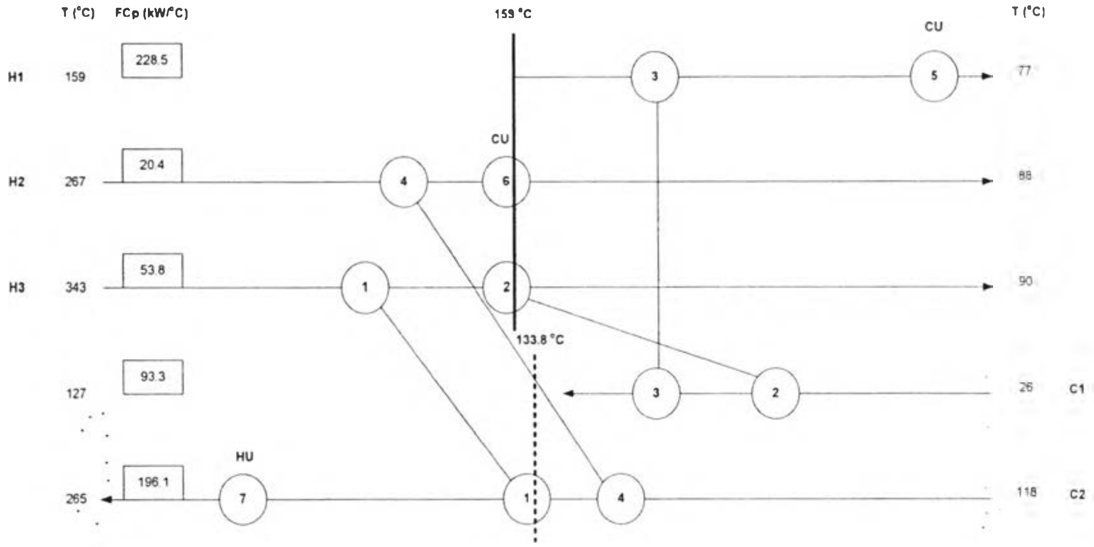


Figure 4.5 Grid diagram for the original heat exchanger network for Example 1.

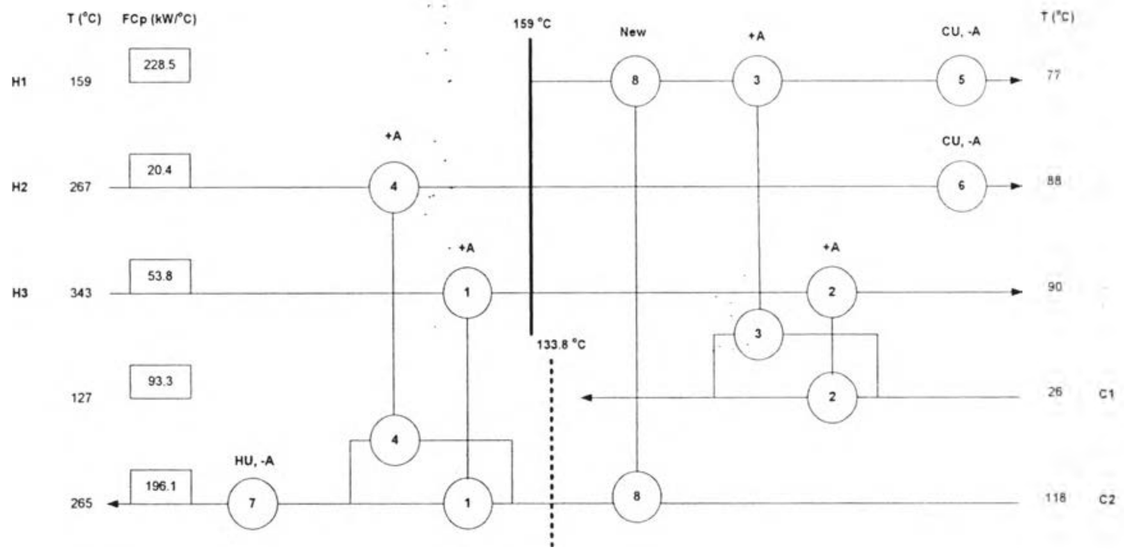
The first step to design the new network is to locate the existing exchangers that transfer heat across the pinch. For Example 1, exchangers 1, 2, 4 and 6 transfer heat across the pinch. Because pinch technology does not allow cross-pinch heat transfer, we must eliminate these exchangers and essentially reuse them. We do this by moving each exchanger to one side of the pinch and then altering the input and target temperatures to ensure that no cross-pinch heat transfer occurs in the new design. As a reminder, the sections above and below the pinch must be analyzed separately. Once we have located the exchangers that transfer heat across the pinch, we need to begin matching one hot stream and one cold stream to each exchanger. We want to reuse as many, if not all, existing exchangers as possible to minimize our capital costs. Furthermore, to ensure that our retrofitted network has the minimum number of heat exchangers possible, we want to maximize the heat transfer of every exchanger between its two matched streams.

To match two streams to an exchanger, we need to look at the heat capacity flow rate (FCp) values. For streams above the pinch (to the left of the dashed line in the grid diagram), $FCp_{HOT} \leq FCp_{COLD}$. Matches below the pinch are made in a similar fashion except $FCp_{COLD} \leq FCp_{HOT}$. These two matching rules ensure that if a stream's target temperatures are not satisfied by process-to-process heat exchange, then the addition of a utility exchanger will satisfy the stream.

Moreover, matching should begin at the pinch. As matches move away from the pinch, these rules become less critical to follow.

After an exchanger has been matched, the heat load must be determined. To do this, we use something called the "Tick-Off" rule which states that we want to satisfy the heat requirements of at least one of the streams connected by each exchanger. This will ensure the minimum number of heat exchangers for the network.

As above procedure we can find one alternative design for above the pinch and three alternative designs for below the pinch which also can be formed as three heat exchanger network as shown below.

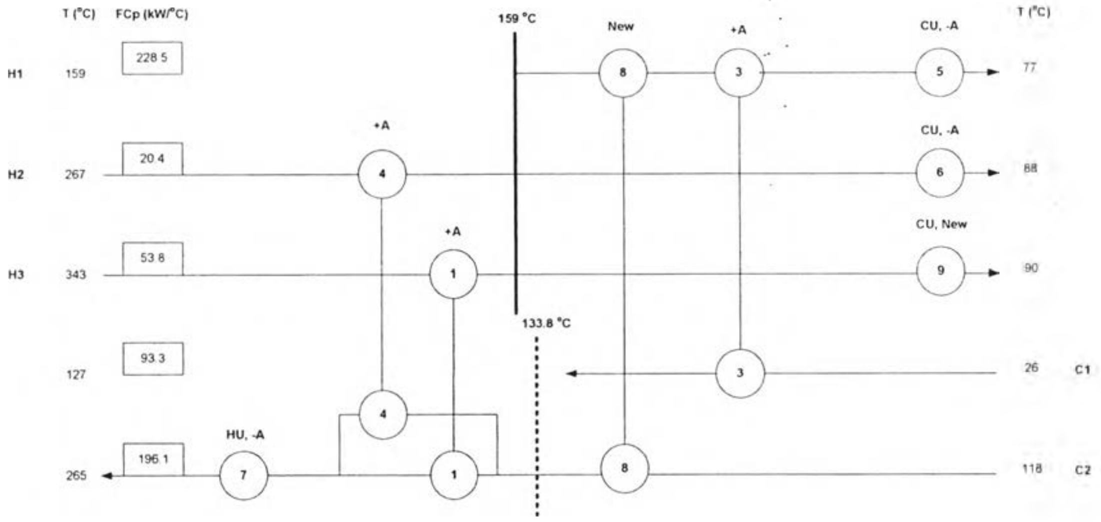


Notation: New exchanger (New), Area addition (+A); New shell (NS), Area reduction (-A)

Figure 4.6 Retrofitted heat exchanger results (1st alternative design at ΔT_{min} =25.2°C).

Table 4.3 Retrofitted heat exchanger results (1^{st} alternative design at ΔT_{min} = 25.2°C)

Heat Exchanger	Original area (m^2)	Load after retrofit (kW)	Retrofit area (m^2)	Area change (m^2)	Remarks
1	609.70	9899.20	858.19	248.49	Area addition (new shell)
2	579.20	3712.20	857.70	278.50	Area addition (new shell)
3	1008.50	5711.10	1125.13	116.63	Area addition
4	117.96	2203.20	264.70	146.74	Area addition (new shell)
5	787.50	9927.52	639.96	-147.54	Area reduction
6	104.60	1448.4	82.96	-21.64	Area reduction
7	246.75	13625.92	197.78	-48.97	Area reduction
8	-	3098.38	530.06	530.06	New exchanger

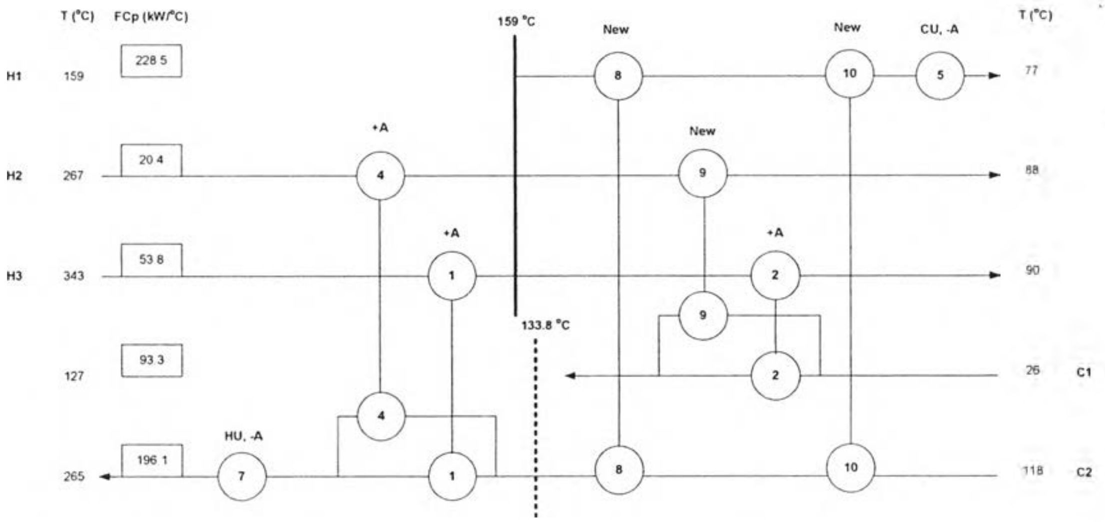


Notation: New exchanger (New), Area addition (+A); New shell (NS), Area reduction (-A)

Figure 4.7 Retrofitted heat exchanger results (2^{nd} alternative design at ΔT_{min}= 25.2°C).

Table 4.4 Retrofitted heat exchanger results (2^{nd} alternative design at $\Delta T_{min} = 25.2^{o}C$)

Heat Exchanger	Original area (m^2)	Load after retrofit (kW)	Retrofit area (m^2)	Area change (m^2)	Remarks
1	609.70	9899.20	858.19	248.49	Area addition (new shell)
2	579.20	-	-	-	Non-operation
3	1008.50	9423.30	2088.30	1079.80	Area addition (new shell)
4	117.96	2203.20	264.70	146.74	Area addition (new shell)
5	787.50	6215.32	450.45	-337.05	Area reduction
6	104.60	1448.4	82.96	-21.64	Area reduction
7	246.75	13625.92	197.78	-48.97	Area reduction
8	-	3098.38	530.06	530.06	New exchanger
9	-	3712.2	236.65	236.65	New exchanger



Notation: New exchanger (New), Area addition (+A); New shell (NS), Area reduction (-A)

Figure 4.8 Retrofitted heat exchanger results (3^{rd} alternative design at $\Delta T_{min} = 25.2^{o}C$).

Table 4.5 Retrofitted heat exchanger results (3rd alternative design at $\Delta T_{min} =$ 25.2°C)

Heat Exchanger	Original area (m^2)	Load after retrofit (kW)	Retrofit area (m^2)	Area change (m^2)	Remarks
1	609.70	9899.20	858.19	248.49	Area addition (new shell)
2	579.20	3712.20	857.70	278.50	Area addition (new shell)
3	1008.50	-	-	-	Non-operation
4	117.96	2203.20	264.70	146.74	Area addition (new shell)
5	787.50	11375.92	704.34	-83.16	Area reduction
6	104.60	-	-	-	Non-operation
7	246.75	13625.92	197.78	-48.97	Area reduction
8	-	3098.38	530.06	530.06	New exchanger
9	-	1448.4	622.12	622.12	New exchanger
10	-	4262.70	451.39	451.39	New exchanger

To make the comparison even more fair, retrofitted heat exchanger using pinch technology is compared by considering the economic data presented below.

Table 4.6 Physical properties of HEN for original HEN and Process pinch

		Retrofitted HEN using process pinch		
	Original HEN	1st alternative design	2nd alternative design	3rd alternative design
ΔT_{min} (°C)	43.1	25.2	25.2	25.2
Network area (m^2)	3,454.21	4,556.48	4,709.08	4,486.27
No. of Exchangers	7	8	8	8
Hot Utilities (kW)	17,759	13,625.92	13,625.92	13,625.92
Cold Utilities (kW)	15,510	11,375.92	11,375.92	11,375.92

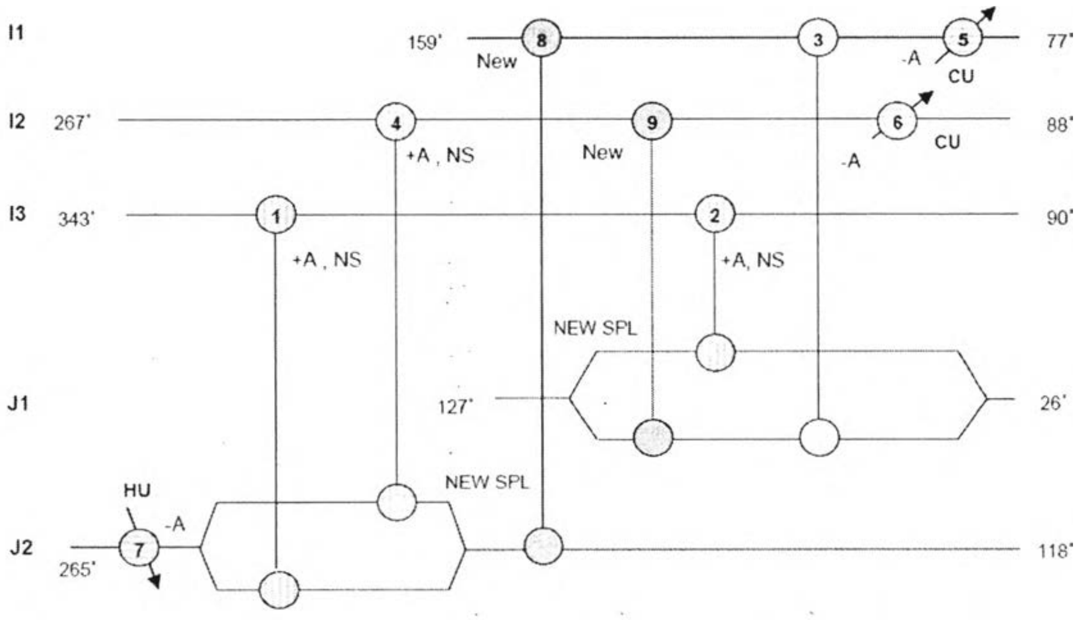
Table 4.7 Cost summary for Example 1 for original HEN and Process pinch

		Retrofitted HEN using process pinch		
	Original HEN	1st alternative design	2nd alternative design	3rd alternative design
Hot Utility Cost ($/yr)	1,687,815.36	1,295,007.4	1,295,007.4	1,295,007.4
Cold Utility Cost ($/yr)	309,889.80	227,290.9	227,290.9	227,290.9
Total capital investment ($)		1,256,493.6	2,045,655.9	1,700,701.3
Energy saving ($/yr)		475,406.8	475,406.8	475,406.8
Total annualized cost ($/yr)		1,853,758.2	2,061,937.2	1,970,939.0
Net present value (over 5 yrs)		545,672.4	-243,489.9	101,464.7
Return on investment (ROI)		37.84%	23.24%	27.95%

The following tables represent the cost comparison among three alternative designs at ΔT_{min} = 25.2 °C. It is also clear that the 1st alternative design has the highest net present value and return on investment as well as the lowest total annualized cost with no suitable loop and path for area/heat duty distribution. Due to the fact that the economic data of the 1st alternative design, the result is high enough without considering the loops and paths adjustment of 2nd and 3rd alternative designs. In addition, loops and paths adjustment can be used to adjust the heat duty and/or area on the exchangers within the loop by shifting the heat around the exchangers. While, the inlet and outlet temperatures remain the same for the adjusted network.

4.1.1.2 MILP Results

The retrofitted design for the MILP which was stated by Nguyen et al. (2010) is shown below in Figure 4.9. The network includes two new exchangers (E8 and E9), an increase in existing exchanger area (E1, E2, and E4), and a reduction in existing exchanger area (E5, E6, and E7). Of the seven existing exchangers only one exchanger remained unchanged (E3). The increase in area to exchangers E8 and E9 was in the form of adding new shells. It is interesting to note that no additional area was added via increasing the area of existing shells. The existing heat exchangers that were increased in area represent heat exchange between process streams; while the heat exchangers that were reduced in area exchanged heat with utilities. These changes in area will produce a more energy efficient design by decreasing the amount of utilities required by the system.



Notation: New exchanger (New), Area addition (+A); New shell (NS), Area reduction (-A), New split (NEW SPL)

Figure 4.9 Retrofitted heat exchanger network for Example 1 (Nguyen et al., 2010).

Table 4.8 Retrofitted heat exchanger results for Example 1 (Nguyen et al., 2010)

Heat exchanger	Original area (m^2)	Load after retrofit (MJ/hr)	Retrofit area (m^2)	Area change (m^2)	
1	610.10	9868.27	966.08	355.97	Area Addition (New Shell)
2	584.15	3743.14	864.59	280.44	
3	1009.87	5222.57	1009.87	0	
4	121.53	2098.53	261.93	140.4	Area Addition (New Shell)
5	852.4	9262.54	644.41	-208.01	Area Reduction
6	95.06	1095.48	70.02	-25.04	
7	246.81	12608.02	184.65	-62.16	
8	0	4251.89	937.84		New Exchangers
9	0	457.59	148.85		

4.1.1.3 *Cost Comparison*

Since Example 1 represents a relatively smaller project, it was decided to show the data for a project life of 5 years. Each method was applied to the same HEN retrofit problem using the same constraints and cost functions to determine the optimal solution.

Table 4.9 Physical properties of HEN for original HEN, process pinch and MILP

		Retrofitted HEN	
	Original HEN	Process pinch	MILP
ΔT_{min} (°C)	43.1	25.2	20.01
Network area (m^2)	3,454.21	4,556.48	5,088.24
No. of Exchangers	7	8	9
Hot Utilities (kW)	17,759	13,625.92	12,608
Cold Utilities (kW)	15,510	11,376	10,358

Table 4.10 Cost summary for Example 1

		Retrofitted HEN	
	Original HEN	Process pinch	MILP
Hot Utility Cost ($/yr)	1,687,815.36	1,295,007.40	1,198,264
Cold Utility Cost ($/yr)	309,889.80	227,290.90	206,953
Total capital investment ($)		1,256,493.60	1,730,945
Energy saving ($/yr)		475,406.80	577,192
Total annualized cost ($/yr)		1,853,758.20	1,861,835.93
Net present value (over 5 yrs)		545,672.40	457,066.92
Return on investment (ROI)		37.84%	33.35%

The following tables represent the cost comparison between the two methodologies. It is clear that the process pinch has the highest net present value and the return on investment as well as the lowest total annualized cost.

As above result, it is apparent that process pinch design is still a powerful procedure to do HEN retrofit which extremely depends on the selection of the best network from all possibilities. However, the MILP allows the user to quickly and easily change parameters that would allow the evaluation of a numerous scenarios.

4.2 Example 2

The second problem is adapted from Barbaro et. al (2005). This problem is the retrofitting of a crude distillation unit. The network consists of 18 streams and 18 exchangers. The current design uses two hot utilities and three cold utilities. The stream data is shown in Table 4.11. The existing exchanger network configuration is shown in Figure 4.10. The existing network does not have splitters. For this example we will compare the results of disallowing heat exchanger relocation. For the case that disallows heat exchanger relocation, alterations in the HEN may only include new exchanger addition and area addition or reduction to existing exchangers. The original HEN consumes 67,988.25 kW of hot utility and 75,076.08 kW of cold utility. Table 4.12 identifies the existing exchangers' original areas, which were calculated using the log mean temperature difference. The amount and costs of each utility used is shown in Table 4.13. The results will be compared for a project life of 5 years and presented in the discussion section. 350 working days per year is assumed.

The maximum values of area addition and reduction that can be made to existing shells are 10% and 40% of the corresponding existing area; respectively (except for the two exchangers E5 & E12 serving the match I5.J1 where the corresponding percentages are 20% and 30%). The maximum area per shell is 5,000 (m^2); the maximum number of shells per exchanger is 4. This problem is also disallowed all hot streams and C3 cold stream splitting. The model was run maximizing the net present value. The pair of exchangers (E10, E11) and the three exchangers (E12, E1, and E5) are not allowed to change their relative order (although E12 and E5 are allowed to switch position. The cost relations for area adjustment for Example 2 are shown Equation 4.5, 4.6, 4.7 and 4.8. A cost is assigned to splitting of \$20,000.

$$\text{Heat exchanger cost (\$)} = 26{,}460 + [389\times \text{Area } (m^2)] \tag{4.5}$$

$$\text{Area addition cost (\$)} = 13{,}230 + [857\times \text{Area}_{\text{added}}(m^2)] \tag{4.6}$$

$$\text{Area reduction cost (\$)} = 13{,}230 + [5\times \text{Area}_{\text{reduced}}\ (m^2)] \tag{4.7}$$

$$\text{New shell} = 26{,}460 + [857\times \text{Area}_{\text{shell}}\ (m^2)] \tag{4.8}$$

Table 4.11 Stream properties for Example 2 (Nguyen et al., 2010)

Stream	F Ton/hr	T in °C	T out °C	Cp kJ/kg.°C	H MJ/hr.m^2.°C
I1	155.1	319.4	244.1	3.161	4.653
I2	5.695	73.24	30	4.325	18.211
I3	251.2	347.3	202.7	3.02	3.210
		202.7	45	2.573	2.278
I4	151.2	263.5	180.2	2.930	4.894
I5	26.03	297.4	203.2	3.041	4.674
		203.2	110	2.689	3.952
I6	86.14	248	147.3	2.831	4.835
		147.3	50	2.442	3.800
I7	91.81	73.24	40	2.262	4.605
I8	63.99	231.8	176	2.854	5.023
		176	120	2.606	4.846
I9	239.1	167.1	116.1	2.595	4.995
		116.1	69.55	2.372	4.880
I10	133.8	146.7	126.7	6.074	1.807
		126.7	99.94	4.745	3.373
		99.94	73.24	9.464	6.878
HU11		250	249		21.600
HU12		1000	500		0.400
J1	519	30	108.1	2.314	1.858
		108.1	211.3	2.645	2.356
		211.3	232.2	3.34	2.212
J2	496.4	232.2	343.3	3.540	2.835
J3	96.87	226.2	228.7	13.076	11.971
		228.7	231.8	15.808	11.075
CU4		20	25		13.500
CU5		124	125		21.600
CU6		174	175		21.600

Table 4.12 Existing exchangers in the network, Example 2 (Nguyen et al., 2010)

Exchanger	Area (m^2)	Heat load (MJ/hr)	Exchanger	Area (m^2)	Heat load (MJ/hr)
1	4303.20	158835.9	10	80.2	3838.9
2	63.80	6903.1	11	685.70	56093.6
3	33.29	17173.8	12	40.00	5930.9
4	4.06	1191.5	13	182.39	58042.3
5	26.79	3018.8	14	101.47	36903.2
6	24.6	2356.9	15	93.87	36917.4
7	5.87	1065.0	16	288.97	67053.1
8	146.59	45024.5	17	52.24	7913.8
9	1214.40	101545.2	18	976.4	135298.7

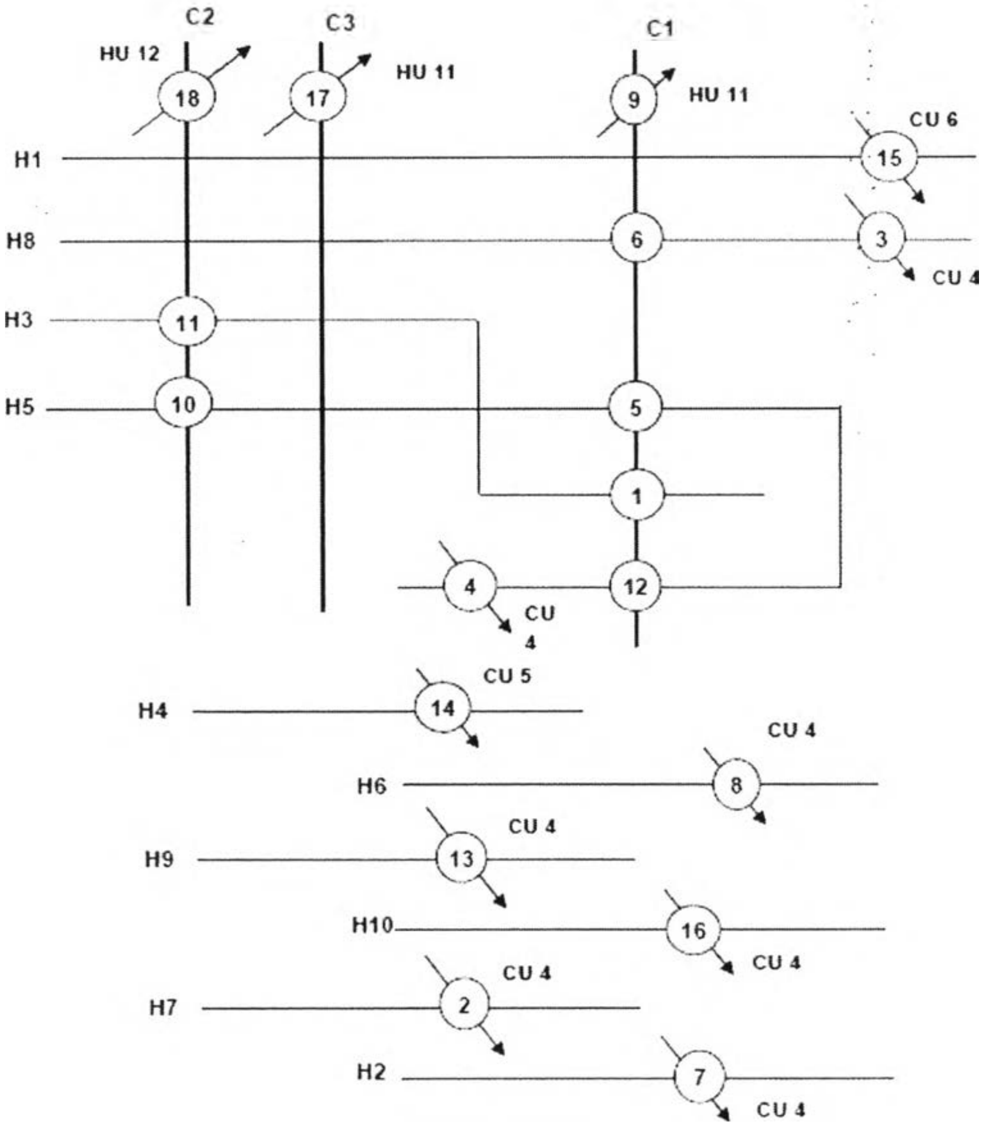


Figure 4.10 Original heat exchanger network for Example 2 (Nguyen et al., 2010).

Table 4.13 Utilities in the original network (Nguyen et al., 2010)

Hot utility	Cost (cent/MJ)	Amount (MJ/hr)	Cold utility	Cost (cent/MJ)	Amount (MJ/hr)
HU11	0.2351	109459	CU4	0.0222	196453.3
HU12	0.4431	135298.7	CU5	0.0773	36903.2
			CU6	0.1518	36917.4
Total hot utilities (MJ/hr)		244757.7	Total cold utilities (MJ/hr)		270273.9

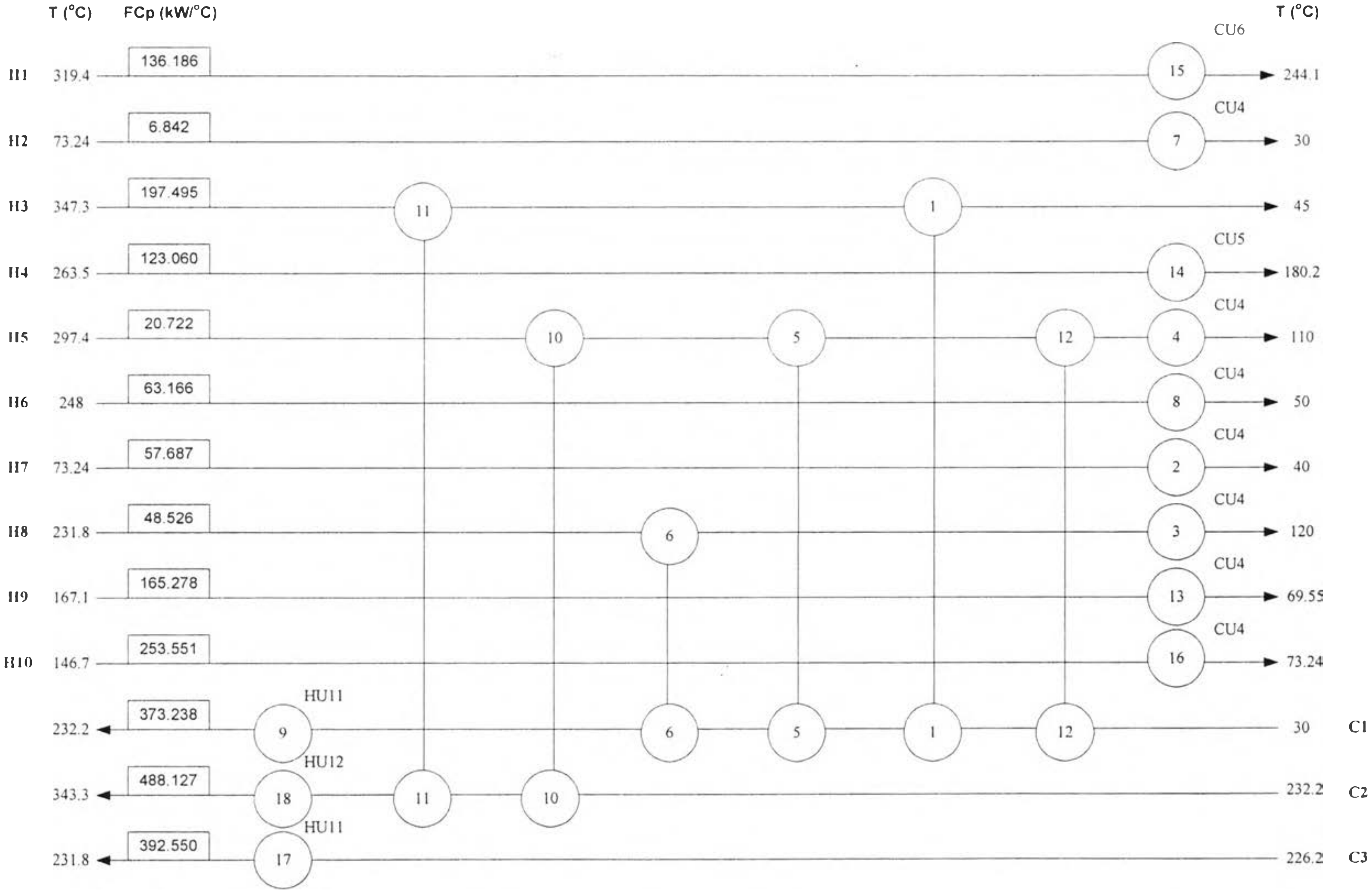


Figure 4.11 Grid diagram of Example 2.

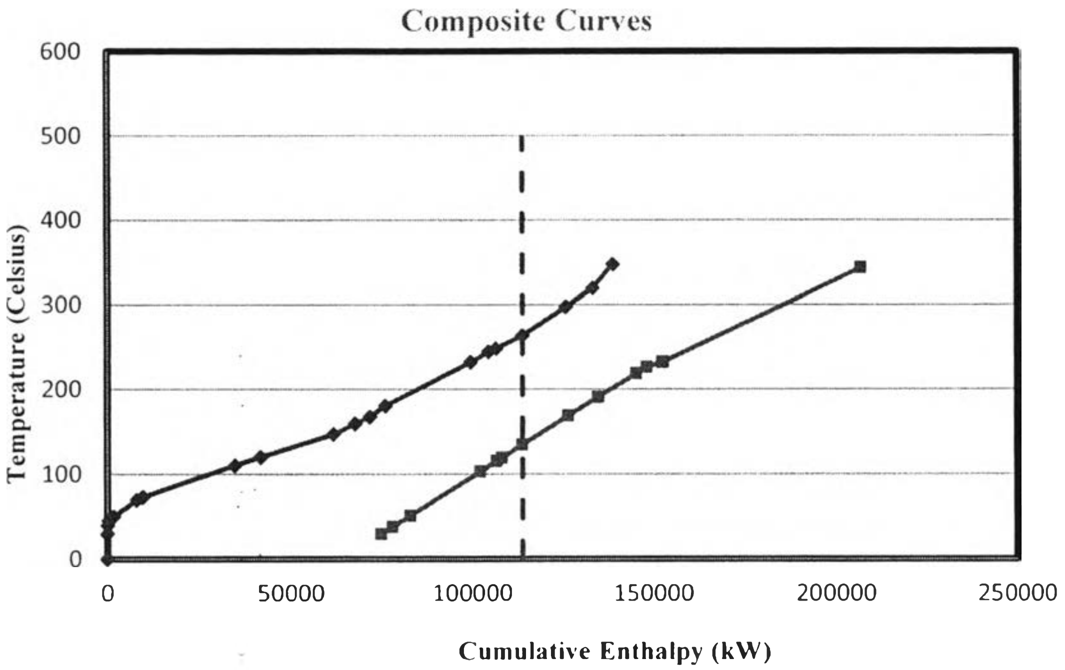


Figure 4.12 Composite curves of the existing HEN.

4.2.1 Discussion

In this section the results for the retrofitted design of the MILP and process pinch are compared. Each method was applied to the same HEN retrofit problem using the same constraints and cost functions. This scenario allows each methodology to manipulate the area of existing exchangers as well as adding new exchangers and introducing split streams.

4.2.1.1 Process Pinch Results

The ΔT_{min} maximizing the ideal NPV was determined from the graph below. It shows the maximum NPV of $18.300,099.7 occurs at a ΔT_{min} of 13 °C with hot and cold utility savings of 45,675.91 kW.

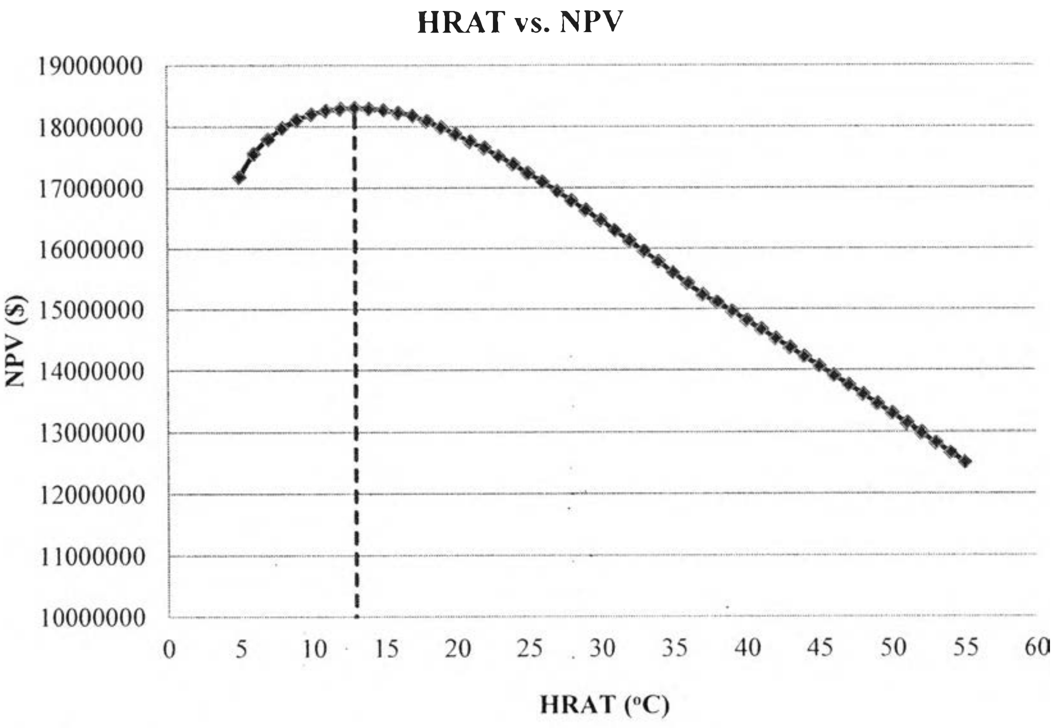


Figure 4.13 HRAT versus NPV.

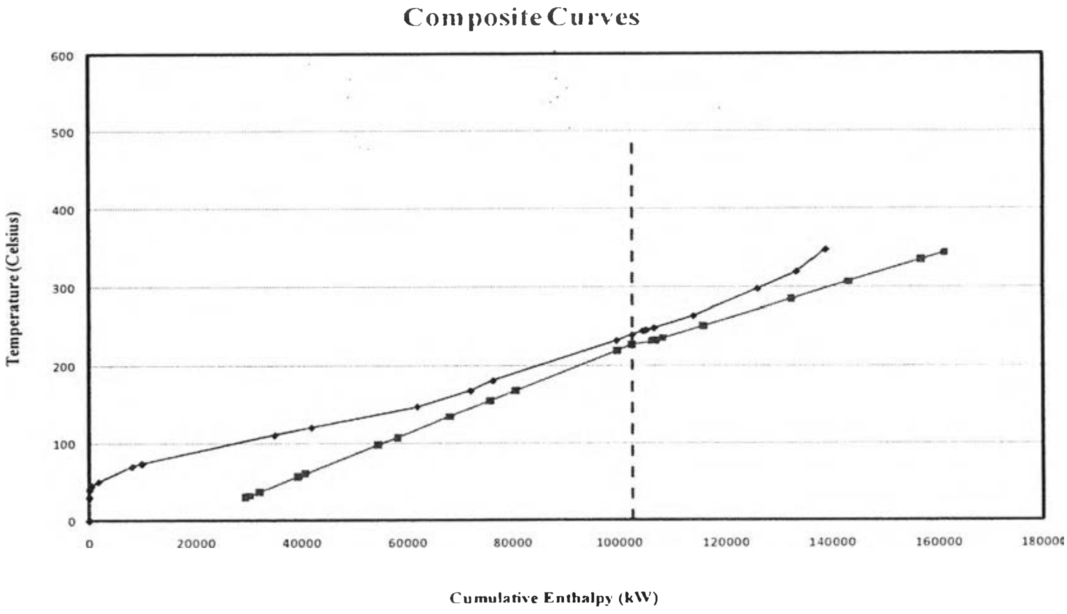


Figure 4.14 Composite curves of HEN retrofit which maximize NPV at a ΔT_{min} of 13°C.

Now that the optimum ΔT_{min} value has been determined, the next step is to generate the stream matches for heat exchange in the new network. To do this, a grid diagram of the process is analyzed with the pinch temperature represented as two vertical lines at the middle of the grid. For this section, Example 2 will be used to demonstrate how to match streams to exchangers. The grid diagram for the retrofitted network of Example 1 is illustrated in Figure 4.15.

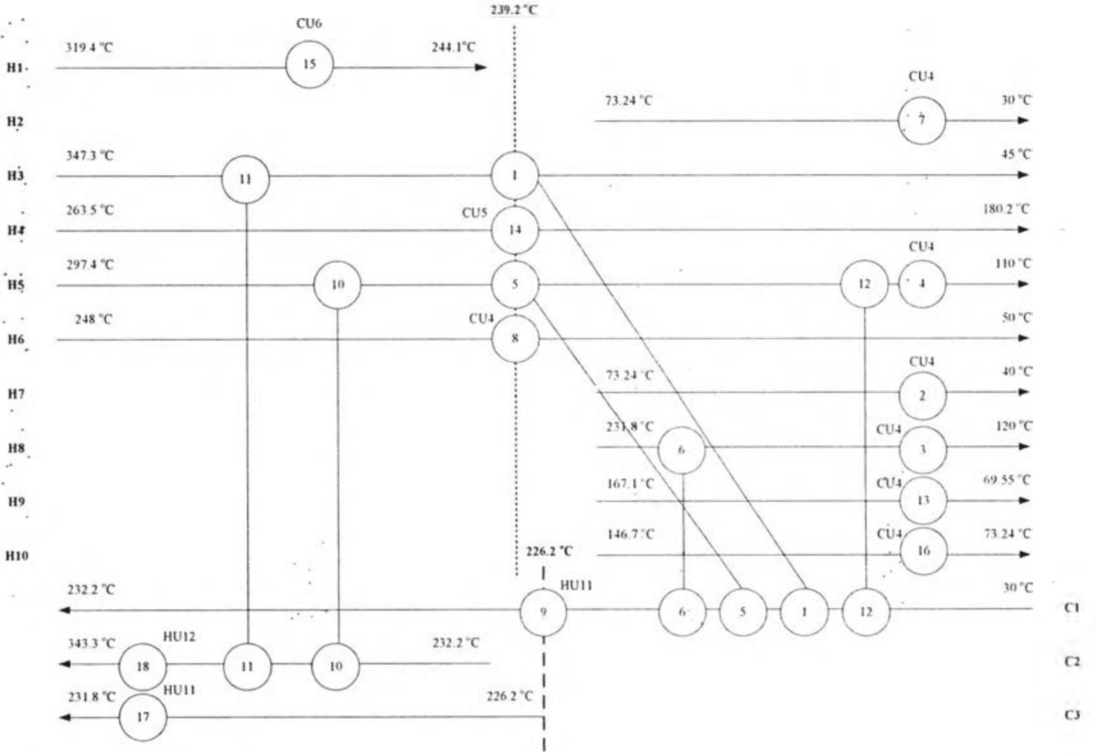


Figure 4.15 Cross pinch grid diagram for Example 2.

The first step to design the new network is to locate the existing exchangers that transfer heat across the pinch. For Example 2, exchangers 1, 5, 8, 9, 14 and 15 transfer heat across the pinch. Because pinch technology does not allow cross-pinch heat transfer, we must eliminate these exchangers and essentially reuse them. We do this by moving each exchanger to one side of the pinch and then altering the input and target temperatures to ensure that no cross-pinch heat transfer occurs in the new design. As a reminder, the sections above and below the pinch must be analyzed separately. Once we have located the exchangers that transfer heat across the pinch, we need to begin matching one hot stream and one cold stream to each exchanger. We want to reuse as many, if not all, existing exchangers as possible to minimize our capital costs. Furthermore, to ensure that our retrofitted network has the minimum number of heat exchangers possible, we want to maximize the heat transfer of every exchanger between its two matched streams.

To match two streams to an exchanger, we need to look at the heat capacity flow rate (FCp) values. Form streams above the pinch (to the left of the dashed line in the grid diagram), $FCp_{HOT} \leq FCp_{COLD}$. Matches below the pinch are made in a similar fashion except $FCp_{COLD} \leq FCp_{HOT}$. These two matching rules ensure that if a stream's target temperatures are not satisfied by process-to-process heat exchange, then the addition of a utility exchanger will satisfy the stream. Moreover, matching should begin at the pinch. As matches move away from the pinch, these rules become less critical to follow.

After an exchanger has been matched, the heat load must be determined. To do this, we use something called the "Tick-Off" rule which states that we want to satisfy the heat requirements of at least one of the streams connected by each exchanger. This will ensure the minimum number of heat exchangers for the network.

As above procedure we can find 3 alternative designs for above the pinch and 3 alternative designs for below the pinch as shown below which also can be formed as 9 heat exchanger network.

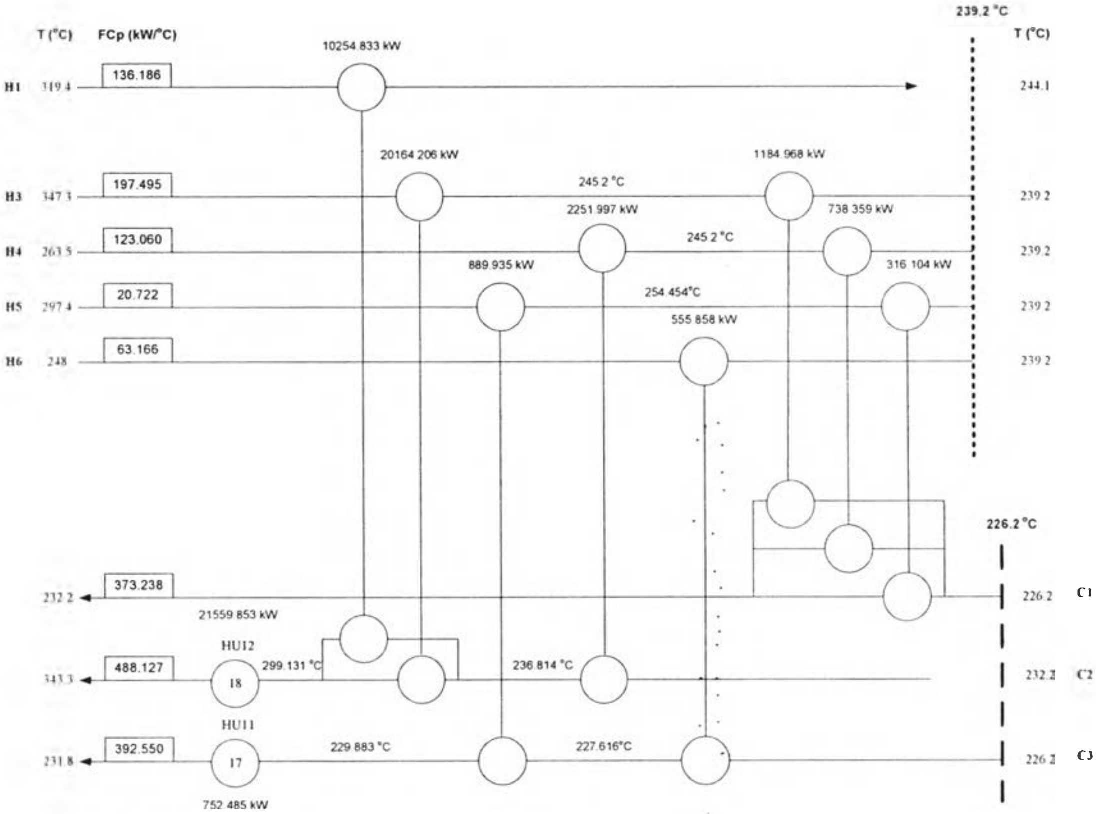


Figure 4.16 Above pinch retrofitted results (1st alternative design at $\Delta T_{min} = 13\ ^{o}C$).

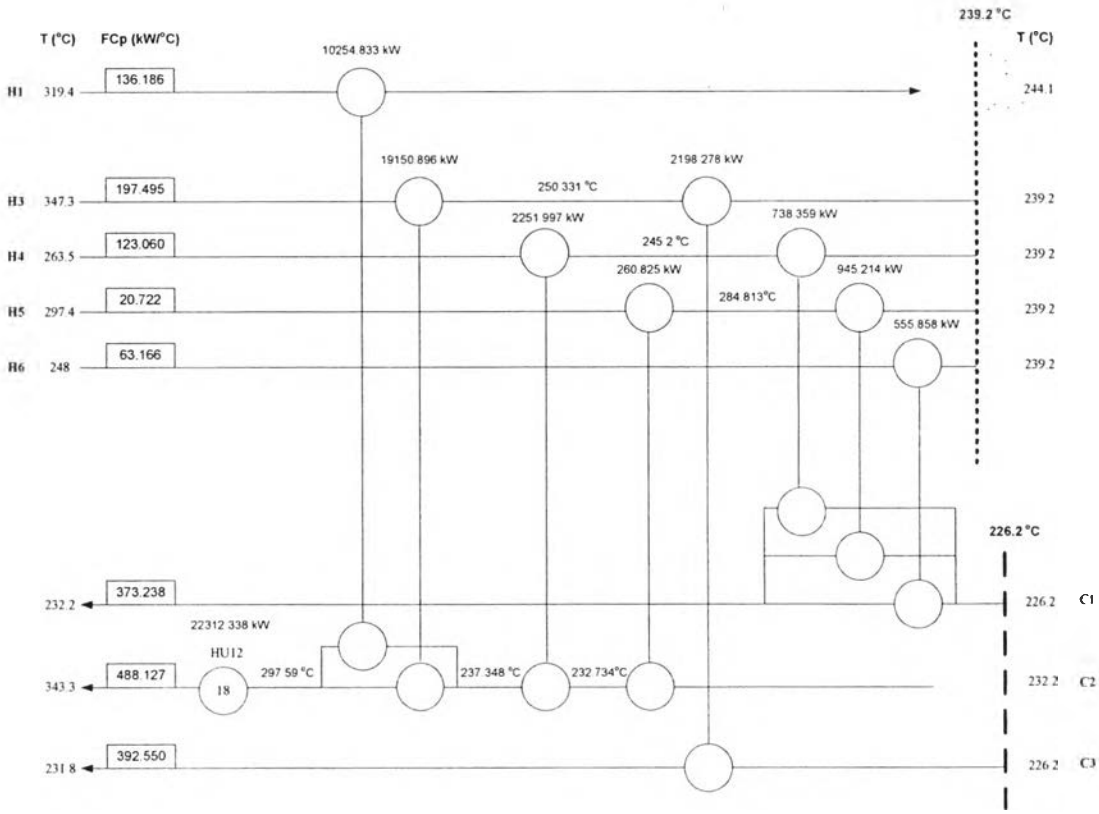


Figure 4.17 Above pinch retrofitted results (2nd alternative design at $\Delta T_{min} = 13\ ^{o}C$).

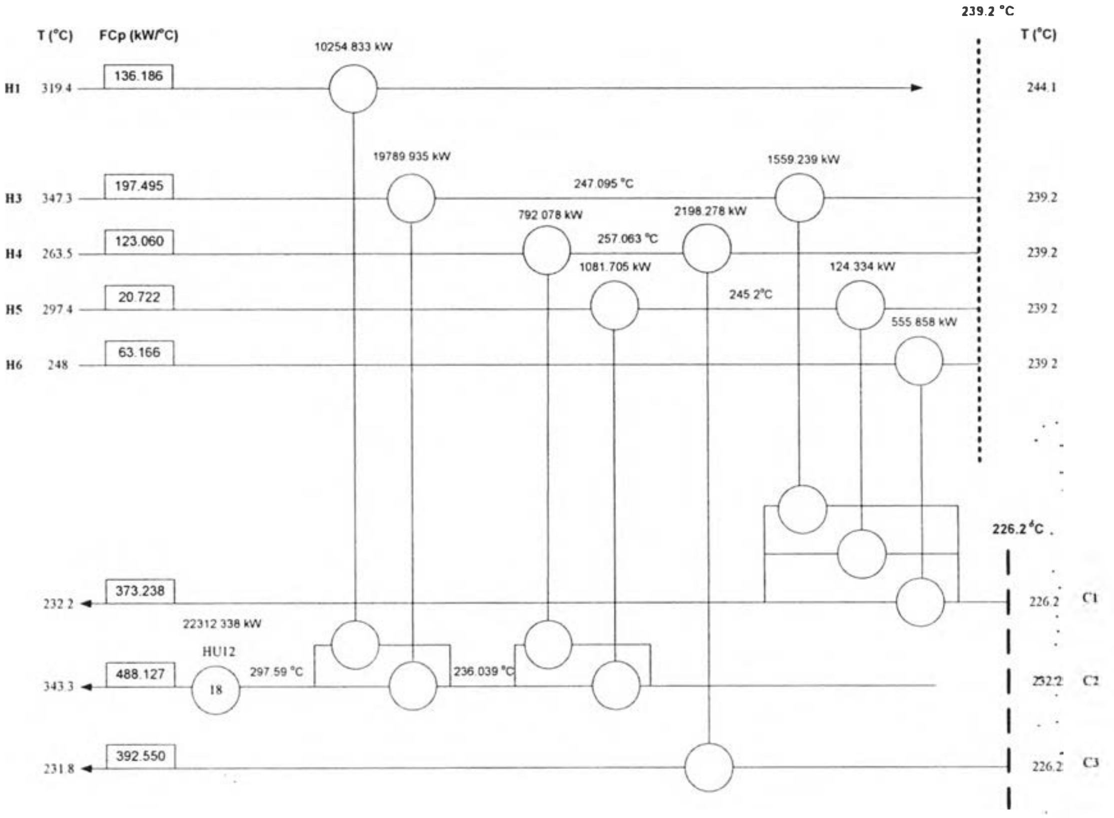


Figure 4.18 Above pinch retrofitted results (3rd alternative design at ΔT$_{min}$ = 13 °C).

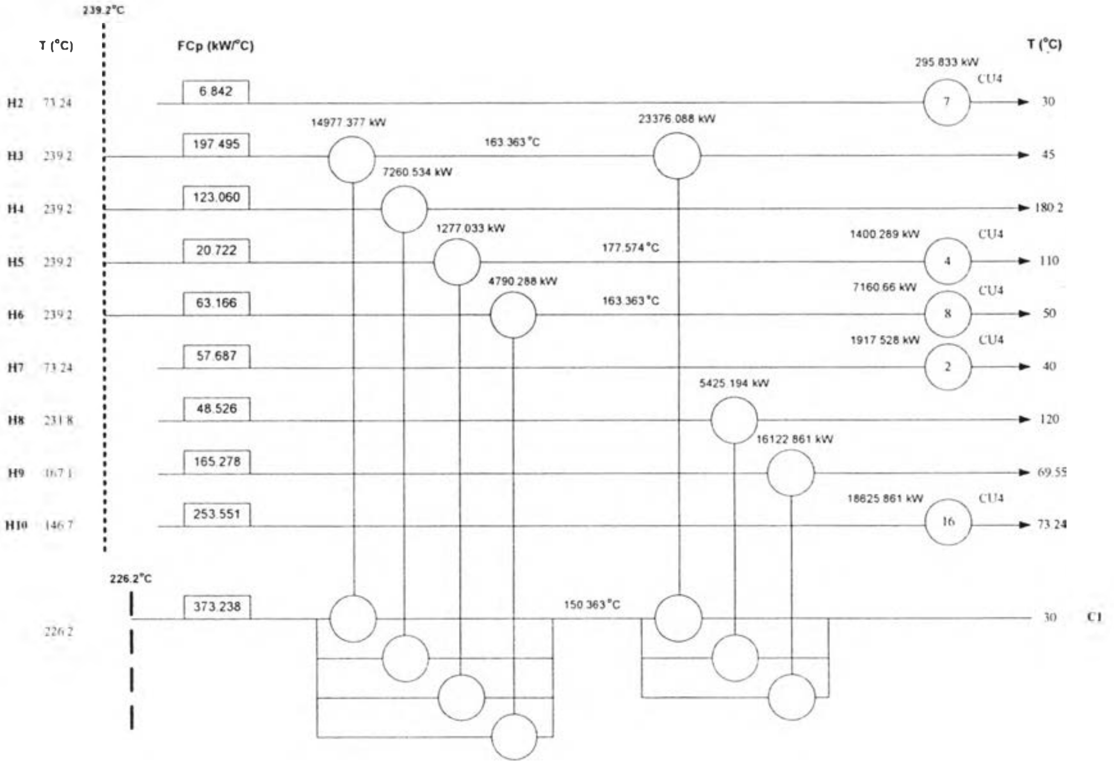


Figure 4.19 Below pinch retrofitted results (1st alternative design at ΔT$_{min}$ = 13 °C).

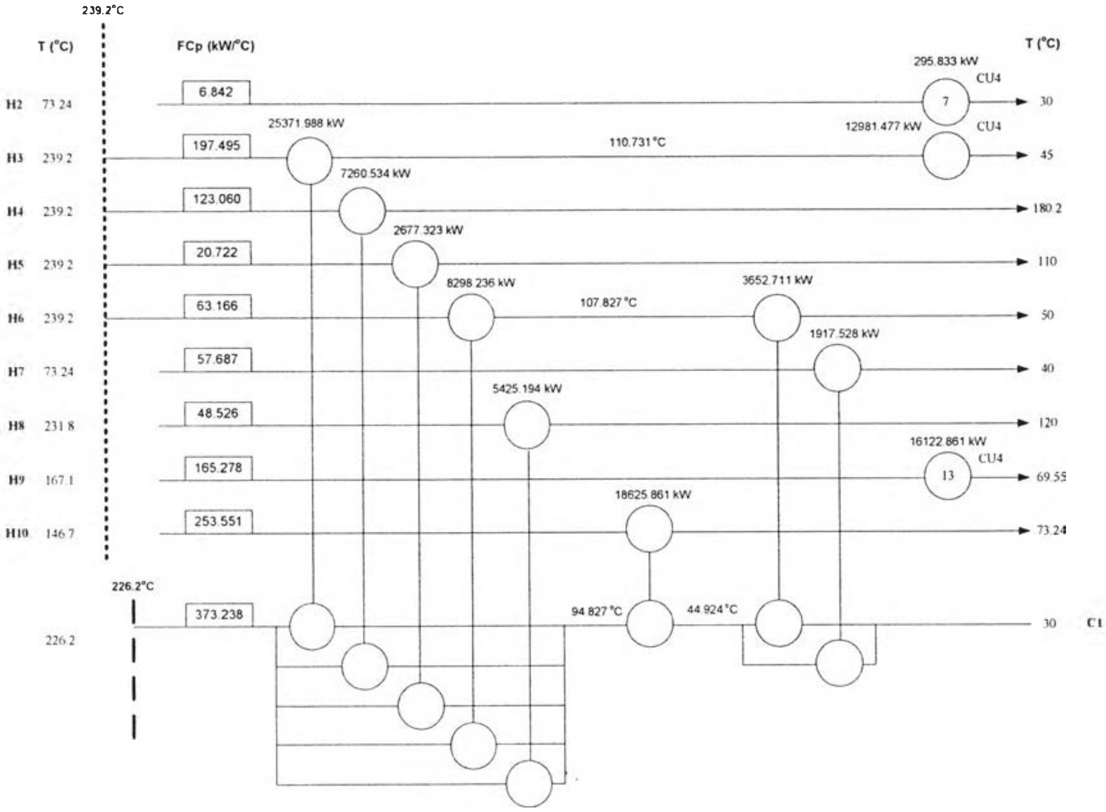


Figure 4.20 Below pinch retrofitted results (2nd alternative design at $\Delta T_{min} = 13\ ^{o}C$).

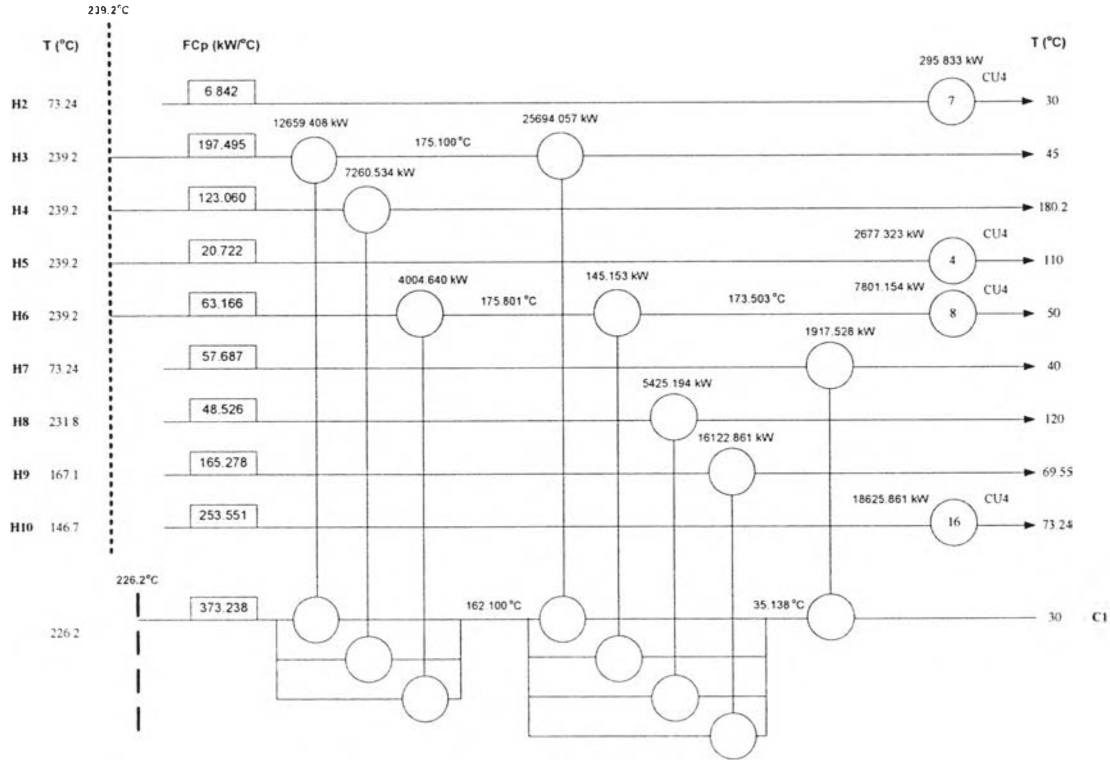


Figure 4.21 Below pinch retrofitted results (3rd alternative design at $\Delta T_{min} = 13\ ^{o}C$).

All above and below pinch designs can be formed as 9 heat exchanger networks. By doing this, we begin with the 1st network which combines the 1st above and the 1st below pinch design. Then, the 2nd network is the combination of the 2nd above and the 1st below pinch design. After that, the 3rd above and the 1st below pinch design are combined to be the 3rd network. So, we do the same procedure until we got 9 retrofitted heat exchanger networks.

As done in Example one, this problem is also compared by considering the economic data presented below.

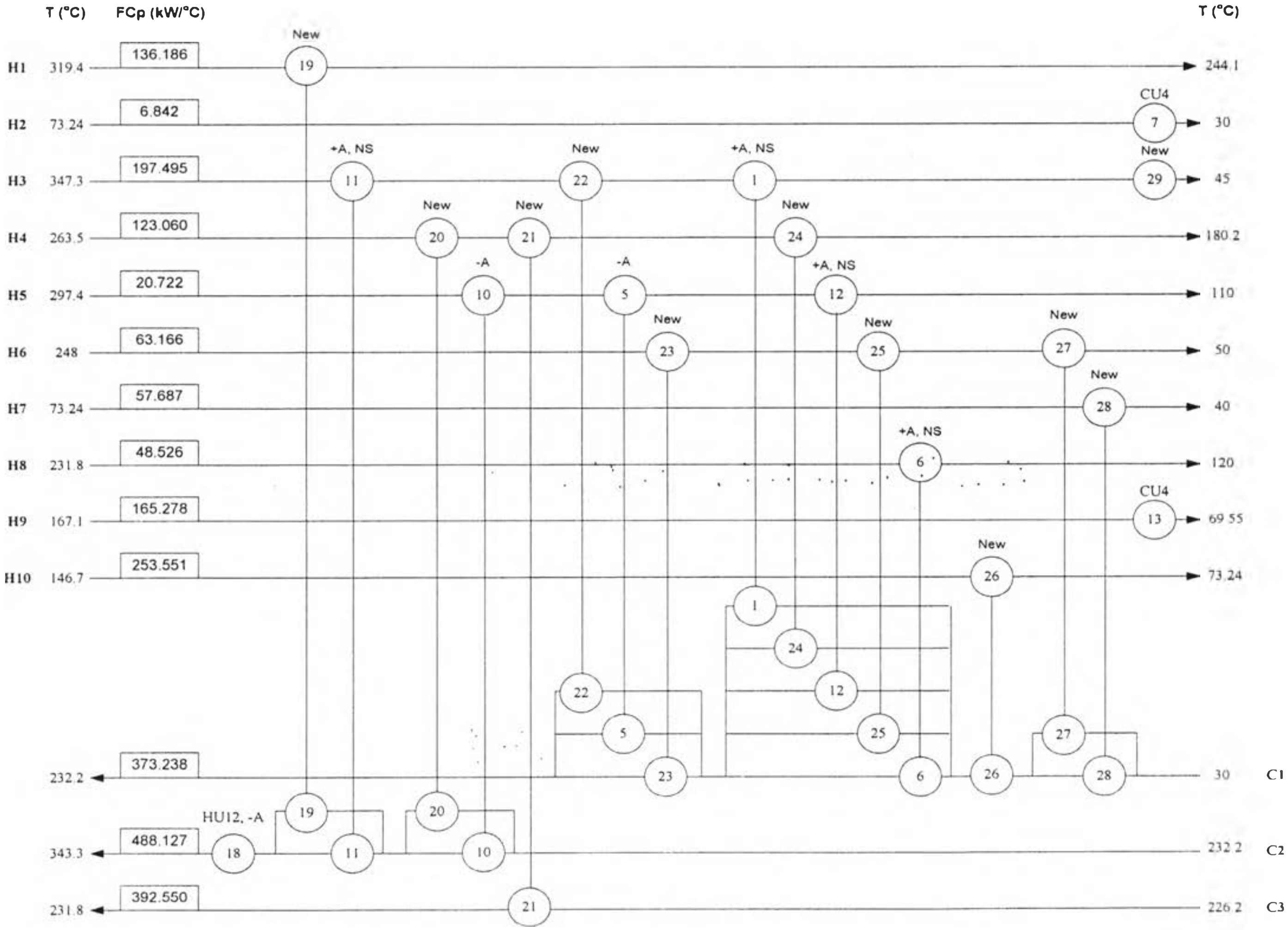
Table 4.14 Physical properties of HEN for original HEN and Process pinch retrofit

	ΔT_{min} (^oC)	Network area (m^2)	No. of Exchangers	Hot Utilities (kW)	Cold Utilities (kW)
Original HEN	128.89	8,323.82	18	67,988.25	75,076.08
1st alternative design	13	16,862.44	22	22,312.34	29,400.17
2nd alternative design	13	16,405.63	21	22,312.34	29,400.17
3rd alternative design	13	16,386.54	21	22,312.34	29,400.17
4th alternative design	13	16,708.70	21	22,312.34	29,400.17
5th alternative design	13	15,935.10	20	22,312.34	29,400.17
6th alternative design	13	15,971.78	20	22,312.34	29,400.17
7th alternative design	13	20,195.55	22	22,312.34	29,400.17
8th alternative design	13	19,783.81	21	22,312.34	29,400.17
9th alternative design	13	19,761.73	21	22,312.34	29,400.17

Table 4.15 Cost summary for Example 2 for original HEN and Process pinch retrofit

	Hot Utility Cost ($/yr)	Cold Utility Cost ($/yr)	Total capital investment ($)	Energy saving ($/yr)	Total annualized cost ($/yr)	Net present value (over 5 yrs)	Return on investment (ROI)
Original HEN	1,687,815.36	309,889.80					
1st alternative design	2,942,376.22	197,371.58	5,379,312.39	5,134,471.17	4,558,796.85	14,084,374.09	95.45%
2nd alternative design	2,989,706.92	197,371.58	4,930,728.84	5,087,140.47	4,487,792.35	14,353,537.01	103.17%
3rd alternative design	2,989,706.92	197,371.58	4,890,794.37	5,087,140.47	4,477,257.74	14,393,471.48	104.01%
4th alternative design	2,942,376.22	197,371.58	5,123,316.75	5,134,471.17	4,491,265.85	14,340,369.73	100.22%
5th alternative design	2,989,706.92	197,371.58	4,552,083.36	5,087,140.47	4,387,906.63	14,732,182.50	111.75%
6th alternative design	2,989,706.92	197,371.58	4,533,270.35	5,087,140.47	4,382,943.80	14,750,995.50	112.22%
7th alternative design	2,942,376.22	197,371.58	6,958,725.88	5,134,471.17	4,975,442.15	12,504,960.60	73.79%
8th alternative design	2,989,706.92	197,371.58	6,544,148.49	5,087,140.47	4,913,408.39	12,740,117.36	77.74%
9th alternative design	2,989,706.92	197,371.58	6,502,622.05	5,087,140.47	4,902,453.82	12,781,643.80	78.23%

The following tables represent the cost comparison among 9 alternative designs at ΔT_{min} = 13°C. It is also clear that the 6th alternative design has the highest net present value and return on investment as well as the lowest total annualized. The heat exchanger network retrofit result is illustrated below.



Notation: New exchanger (New), Area addition (+A); New shell (NS), Area reduction (-A)

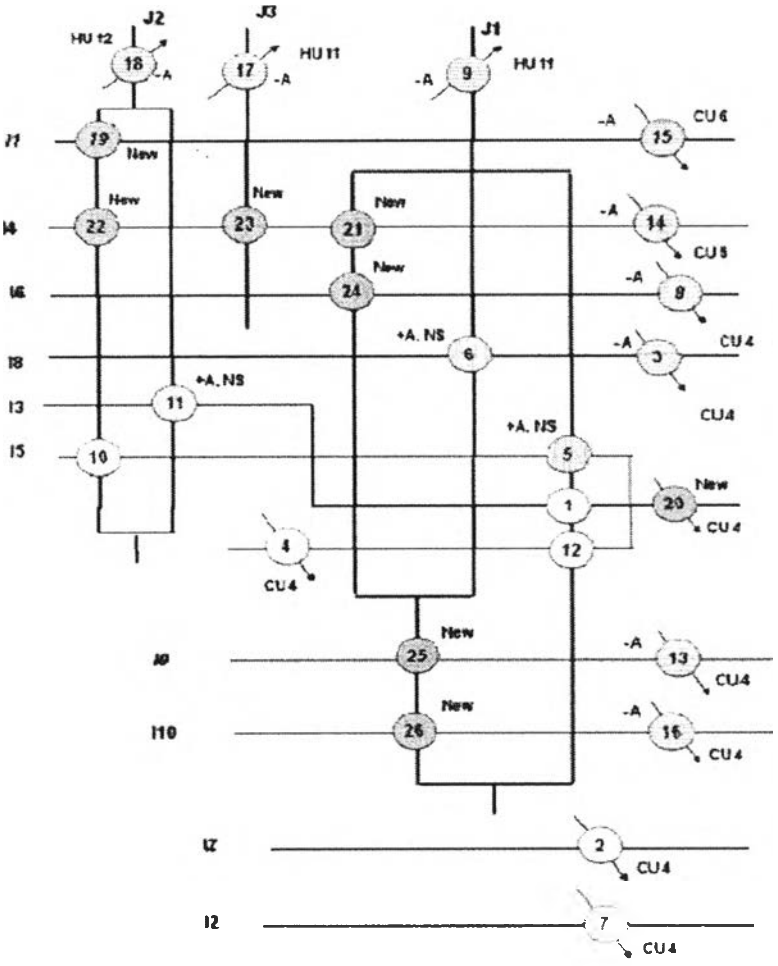
Figure 4.22 Retrofitted heat exchanger results (6th alternative design at $\Delta T_{min} = 13\ ^{o}C$).

Table 4.16 Retrofitted heat exchanger results (6th alternative design at ΔT_{min} = 13°C.)

Heat Exchanger	Original area (m^2)	Load after retrofit (kW)	Retrofit area (m^2)	Area change (m^2)	Remarks
1	4303.20	25371.99	5271.72	968.52	Area addition (new shell)
2	63.80	-	-	-	-
3	33.29	-	-	-	-
4	4.06	-	-	-	-
5	26.79	124.33	24.06	-2.73	Area reduction
6	24.60	5425.19	1004.10	979.50	Area addition (new shell)
7	5.87	295.83	5.87	0.00	-
8	146.59	-	-	-	-
9	1214.40	-	-	-	-
10	80.20	1081.71	70.81	-9.39	Area reduction
11	658.70	19789.94	1987.03	1328.33	Area addition (new shell)
12	40.00	2677.32	479.03	439.03	Area addition (new shell)
13	182.39	16122.86	182.39	0.00	-
14	101.47	-	-	-	-
15	93.87	-	-	-	-
16	288.97	-	-	-	-
17	52.24	-	-	-	-
18	976.40	22312.34	593.70	-382.70	Area reduction
19	-	10254.83	1517.08	-	New exchanger
20	-	792.08	60.77	-	New exchanger
21	-	2198.28	118.48	-	New exchanger
22	-	1559.24	335.08	-	New exchanger
23	-	555.86	97.37	-	New exchanger
24	-	7260.53	456.23	-	New exchanger
25	-	8298.24	1605.07	-	New exchanger
26	-	18625.86	1233.17	-	New exchanger
27	-	3652.71	245.31	-	New exchanger
28	-	1917.53	268.32	-	New exchanger
29	-	12981.48	415.85	-	New exchanger

4.2.1.2 MILP Results

As can be seen in Figure 11 which was stated by Nguyen et al. (2010), splitting is introduced to the two streams J1, J2 and there are eight new exchangers added to the network (exchangers 19 to 26, highlighted by using gray background). Exchangers in the retrofitted network are summarized in Table 7. In addition to eight brand new exchangers, three exchangers are expanded by means of adding new shell: exchangers 5, 6 and 11; the total added area is 3953.65 (m^2). As the result of increased heat recovery; the use of utilities is decreased and all the exchangers involving utilities in the retrofitted network (except exchanger 4) is reduced in area (9 exchangers 3, 8, 9, 13, 14, 15, 16, 17, 18).



Notation: New exchanger (New), Area addition (+A); New shell (NS), Area reduction (-A). New split (NEW SPL)

Figure 4.23 Retrofitted heat exchanger network for Example 2 (Nguyen et al., 2010).

Table 4.17 Retrofitted heat exchanger results for Example 2 (Nguyen et al., 2010)

Ex.	Area (m^2)	Area change (m^2)	Note	Ex.	Area (m^2)	Area change (m^2)	Note
1	4303.20	0		14	60.88	-40.59	Area Red.
2	63.80	0		15	56.32	-37.55	Area Red.
3	19.97	-13.32	Area Red.	16	199.97	-89	Area Red.
4	4.064	0		17	31.34	-20.90	Area Red.
5	77.1	50.27	New shell	18	701.03	-275.37	Area Red.
6	176.76	152.16	New shell	19	328.41	328.41	New Ex.
7	5.87	0.00		20	119.1	119.1	New Ex.
8	107.05	-39.54	Area Red.	21	206.72	206.72	New Ex.
9	728.64	-485.76	Area Red.	22	131.93	131.93	New Ex.
10	80.2	0		23	53.26	53.26	New Ex.
11	2481.93	1796.23	New shell	24	415.82	415.82	New Ex.
12	40.00	0		25	476.83	476.83	New Ex.
13	112.47	-69.93	Area Red.	26	222.92	222.92	New Ex.

4.2.1.3 Cost Comparison

Example 2 represents a relatively larger project; it was also decided to show the data for a project life of 5 years. Each method was applied to the same HEN retrofit problem using the same constraints and cost functions to determine the optimal solution.

Table 4.18 Physical properties of HEN for original HEN, process pinch and MILP

		Retrofitted HEN	
	Original HEN	Process pinch	MILP
ΔT_{min} (°C)	128.89	13	50.09
Network area (m^2)	8,323.82	15,971.78	11,205.53
No. of Exchangers	18	20	26
Hot Utilities (kW)	67,988.25	22,312.34	38,577.14
Cold Utilities (kW)	75,076.08	29,400.17	45,664.97

Table 4.19 Cost summary for Example 2

		Retrofitted HEN	
	Original HEN	Process pinch	MILP
Hot Utility Cost ($/yr)	7,197,511.85	2,989,706.92	4,386,378.00
Cold Utility Cost ($/yr)	1,076,707.12	197,371.58	600,779.40
Total capital investment ($)		4,533,270.35	2,021,622.00
Energy saving ($/yr)		5,087,140.47	3,286,573.00
Total annualized cost ($/yr)		4,382,943.80	5,391,482.00
Net present value (over 5 yrs)		14,750,995.50	10,437,076.14
Return on investment (ROI)		112.22%	162.57%

The following tables represent the cost comparison between the process pinch and the MILP. It is clear that the process pinch method has the highest net present value and lowest total annualized cost. However a small investment of the MILP model gives the highest ROI.

As above result, it is apparent that process pinch design is still a powerful procedure to do HEN retrofit which extremely depends on the selection of the best network from all possibilities. However, the MILP allows the user to quickly and easily change parameters that would allow the evaluation of a numerous scenarios.