CHAPTER IV
RESULTS AND DISCUSSION

There are many various examples presented here to express the optimal heat exchanger network structure with minimum total cost. The problems from previous study, Barbaro A. and M. Bagajewicz, are also illustrated in this chapter. The MILP model was constructed in GAMS and run in a PC with a 2.4 GHz processor and 1 Gb of RAM memory.

4.1 Grass-roots Design for HEN

4.1.1 Problem 4.1 (Problem 4S1, Barbaro's work)

This problem consisting of two hot and two cold process streams, one cooling and one heating utility was reported in Shenoy (1995). The table below shows the details of hot (I) and cold (J) streams of problem 4.1.

Table 4.1 Properties of stream for Problem 4.1

Stream	F Ton/hr	Cp KJ/kg-C	Tin C	Tout C	h MJ/h-m^2-C	Q MJ/hr
I1	10	1	175	45	0.2	1300
I2	40	1	125	65	0.2	2400
I3		1	180	179	0.2	
J1	20	1	20	155	0.2	2700
J2'	15	1	40	112	0.2	1080
J3		1	15	25	0.2	

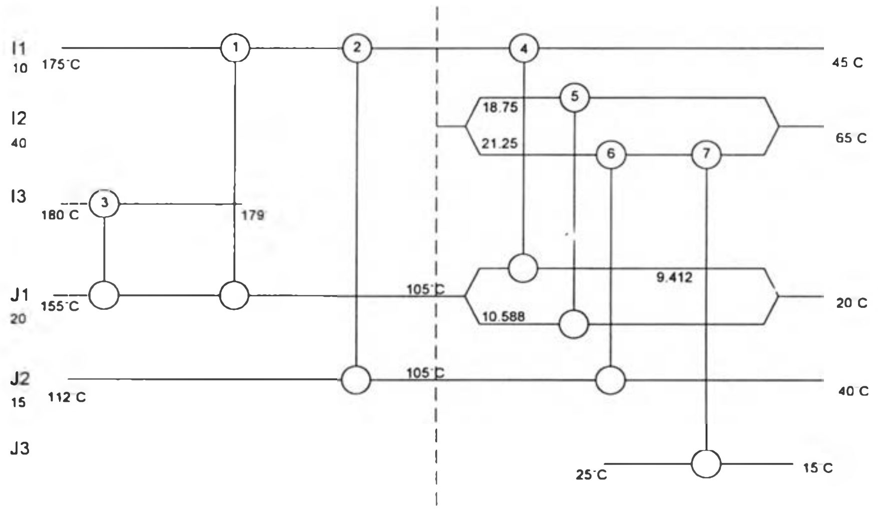
Table 4.2 Cost data for Problem 4.1

Utilities	Cost $/(MJ/hr-yr)
I3	19.75
J3	1.861
Heat Exchanger Cost 5291.9+77.788A $/yr	

Following model testing condition is the minimum approach temperature of 20 °C and the temperature intervals of 26 with two heat transfer zones, the result of heat exchanger network shown in Figure 4.1 and model statistics report that zero gap solution was found in 0.453 second. The new design of heat exchanger network also shows the energy usage consumed in process that totally equal to 605 MJ/hr for hot utility and 525 MJ/hr for cooling utility with $156,886 as the total cost.

Table 4.3 Model statistics for Problem 4.1 at 26 temperature intervals

Model Statistics	
Single Variables	396
Discrete Variables	71
Single Equations	1079
Non Zero Elements	3175
Time to reach global optimal solution (sec)	0.453
Optimality Gap	0.00%



No. of heat exchanger	1	2	3	4	5	6	7
Heat Load (MJ/hr)	395	105	605	800	900	975	525
Area (Prog.), (m^2)	112.794	42.828	158.865	357.03	254.753	346.927	101.273
Area (Actual), (m^2)	99.86	48.38	160.24	357.03	254.75	342.12	113.19

Figure 4.1 Heat exchanger network for Problem 4.1 at 26 temperature intervals.

Additionally, effect of number of temperature intervals in each process streams also need to be studied. Following the process streams properties in the problem 4.1, increasing the number of temperature intervals is simulated and the result is shown in Table 4.4.

Table 4.4 Result of increasing number of temperature intervals for Problem 4.1 (Two heat transfer zones)

No. of Interval	Total Cost $/yr	Total Area m^2	Hot Utility MJ/hr	Cold Utility MJ/hr	Total Utility MJ/hr	Fixed cost $/yr	Area Cost $/yr	Utility Cost $/yr
26	156,886.31	1,374.47	605	525	1,130.00	37,043.30	106,917.27	12,925.78
56	157,305.17	1,379.85	605	525	1,130.00	37,043.30	107,336.08	12,925.78
112	156,069.54	1,363.97	605	525	1,130.00	37,043.30	106,100.42	12,925.78
224	155,765.24	1,360.06	605	525	1,130.00	37,043.30	105,796.19	12,925.78

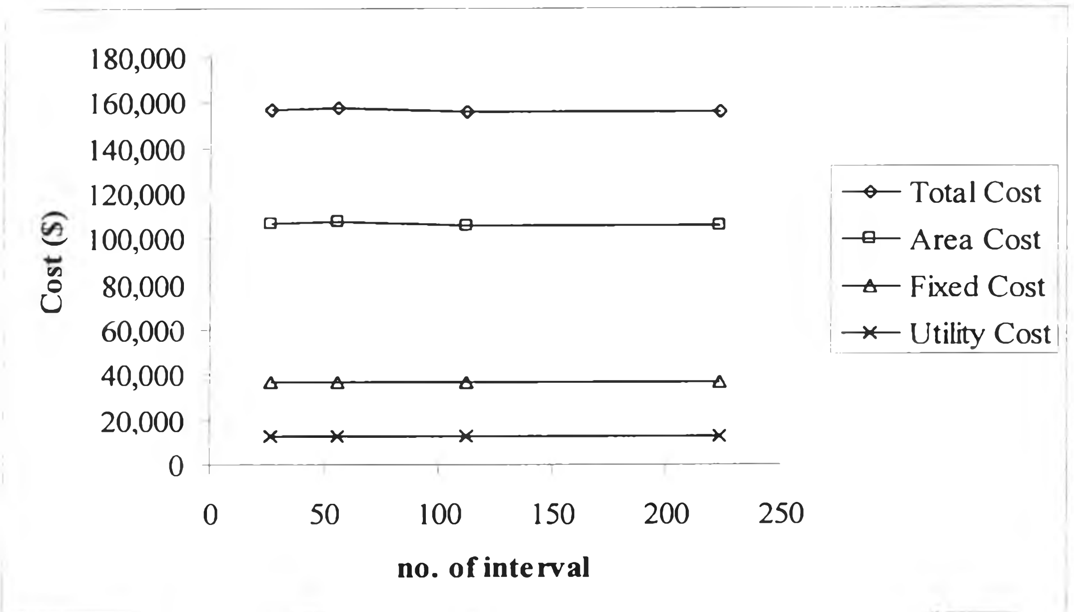


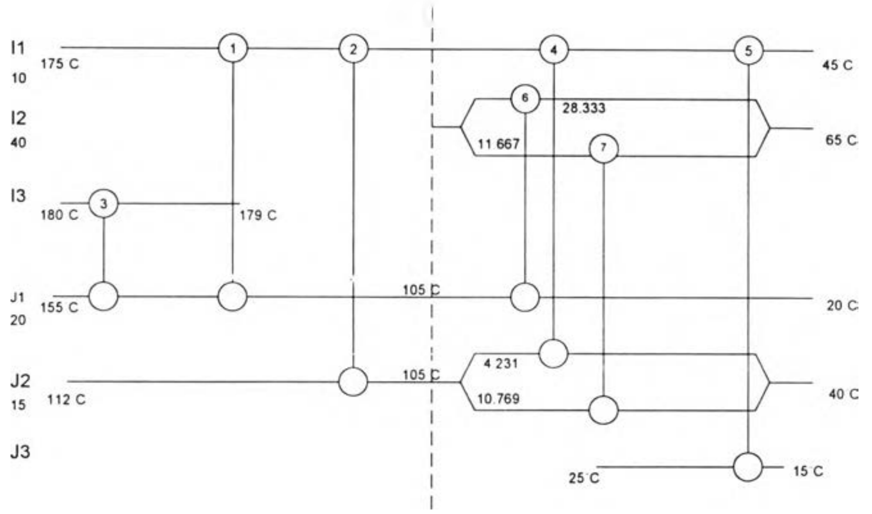
Figure 4.2 Trend of varying the number of temperature intervals for Problem 4.1 (Two heat transfer zones).

The result of the objective function including the utility and fixed and area costs, heat exchanger area, and the total energy usage. Figure 4.2 illustrates the trend of all these values with various number of temperature intervals. All of the number of intervals give the same heat exchanger network structure except the number of interval of 26. Total area given by the model is fairly declined by increasing the number of temperature intervals and each network also consumes constant amount of utility. Moreover, all networks consist of the same number of heat exchanger unit corresponding to the remaining fixed cost when the number of interval changes.

There is a very small variation in the objective function resulting from fluctuation in exchanger area. This variation is decreased by increasing the number of interval. Because, the programming model calculated the area of exchanger by using the amount of heat transfer in each interval, higher interval number gives the accurate area. The exchanger area calculated by programming and the actual area are closer when increasing number of temperature intervals. However, following the Figure 4.2, the objective value eventually seems to be not far from each other, which can be imposed that it gives the stable optimal solution. All network structures are shown in Figure 4.3. Model statistics show that the model also consumes more time to achieve the zero gap solution where the interval number increases. Additionally, the optimal network structures generated from an automatic MILP model correspond to the network structure presented in Barbaro's work.

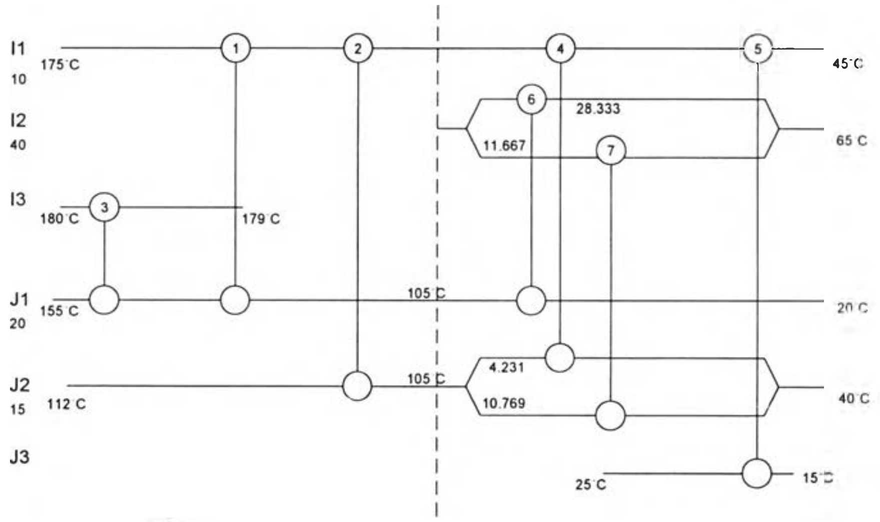
Table 4.5 Model statistics for Problem 4.1 (Two heat transfer zones)

No. of Interval	26	56	112	224
Single Variables	396	994	2650	8001
Discrete Variables	71	139	268	526
Single Equations	1079	2479	5112	10399
Non Zero Elements	3175	8359	20719	55711
Time to reach global optimal solution (sec)	0.453	8.125	165.718	1291.41
Optimality Gap	0.00%	0.00%	0.00%	0.00%



No. of heat exchanger	1	2	3	4	5	6	7
Heat Load (MJ/hr)	395	105	605	275	525	1700	700
Area (Prog.), (m^2)	101.357	47.549	160.033	79.193	109.217	562.141	320.364
Area (Actual), (m^2)	99.86	48.38	160.24	77.44	109	551.43	312.4

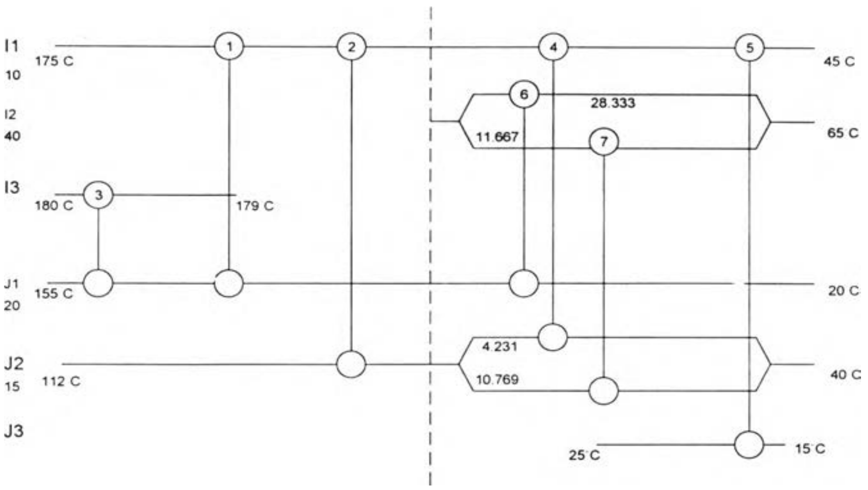
(a) 56 intervals



No. of heat exchanger	1	2	3	4	5	6	7
Heat Load (MJ/hr)	395	105	605	275	525	1700	700
Area (Prog.), (m^2)	100.062	48.394	160.229	77.935	109.05	554.032	314.267
Area (Actual), (m^2)	99.86	48.38	160.24	77.44	109	551.43	312.4

(b) 112 intervals

Figure 4.3 Heat exchanger network for Problem 4.1 with two zones of heat transfer at different number of intervals.



No. of heat exchanger	1	2	3	4	5	6	7
Heat Load (MJ/hr)	395	105	605	275	525	1700	700
Area (Prog.). (m^2)	99.922	48.372	160.235	77.577	109.012	552.08	312.86
Area (Actual). (m^2)	99.86	48.38	160.24	77.44	109	551.43	312.4

(c) 224 intervals

Figure 4.3 (Cont.) Heat exchanger network for Problem 4.1 with two zones of heat transfer at different number of intervals.

To completely study the optimal heat exchanger network for the problem 4.1, operating at one heat transfer zone need to be considered. Table 4.6 explains the result given by simulating the model at any intervals. According to these results, at the same number of temperature interval, the total cost of the model operated only one heat transfer zone is less than the model operated with two heat transfer zones. However, utility usage for the one zone operating is larger than one for two zones because one zone network has smaller exchanger area and number of units. The fixed and area costs for the model operated with one heat transfer zone are smaller, causing the total annualized cost go down.

The heat exchanger network structures for one heat transfer zone with different the number of intervals are shown in Figure 4.5. The structures are not quite much different even increasing the number of intervals, if the 26 intervals case is neglected. The network consisted of five exchanger units. The objective function decreases when the number of intervals enhances from 26 to 56 but remains closer to each other, very small reduction, for the case where number of interval higher than 56. It results from reducing in the exchanger area and number of units that lower charge in area cost and fixed cost. Precisely, utility cost climbs up in order to satisfy the temperature target of hot and cold stream because of a tiny area of exchanger. Decreasing in heat exchanger area calculated by the program certainly comes from different flow rate splitting of the cold utility. However, there is a small variation of area calculation from programming model. This variation can be diminished by enhancing the number of temperature intervals. Although the objective value is not constant, it finally goes to the similarly value or insignificant difference.

Table 4.6 Result of increasing number of temperature intervals for Problem 4.1 (One heat transfer zone)

No. of Interval	Total Cost $/yr	Total Area m^2	Hot Utility MJ/hr	Cold Utility MJ/hr	Total Utility MJ/hr	Fixed Cost $/yr	Area Cost $/yr	Utility Cost $/yr
26	151,917.23	1,123.93	1,032.00	952.00	1,984.00	42,335.20	87,428.42	22,153.67
56	134,099.68	1,057.50	1,181.25	1,101.25	2,282.50	26,459.50	82,261.12	25,379.11
112	133,805.89	1053.73	1,181.25	1,101.25	2,282.50	26,459.50	81,967.55	25,379.11
160	133,774.74	1,052.98	1,182.50	1,102.50	2,285.00	26,459.50	81,909.05	25,406.13
180	133,748.68	1,057.21	1,166.06	1,086.06	2,252.12	26,459.50	82,238.33	25,050.90
192	133,734.31	1,055.46	1,171.70	1,091.70	2,263.40	26,459.50	82,102.04	25,172.69

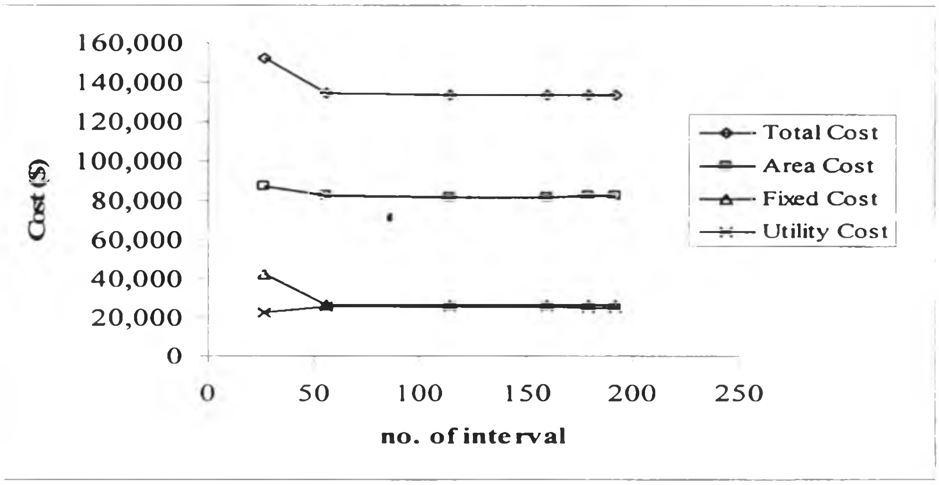
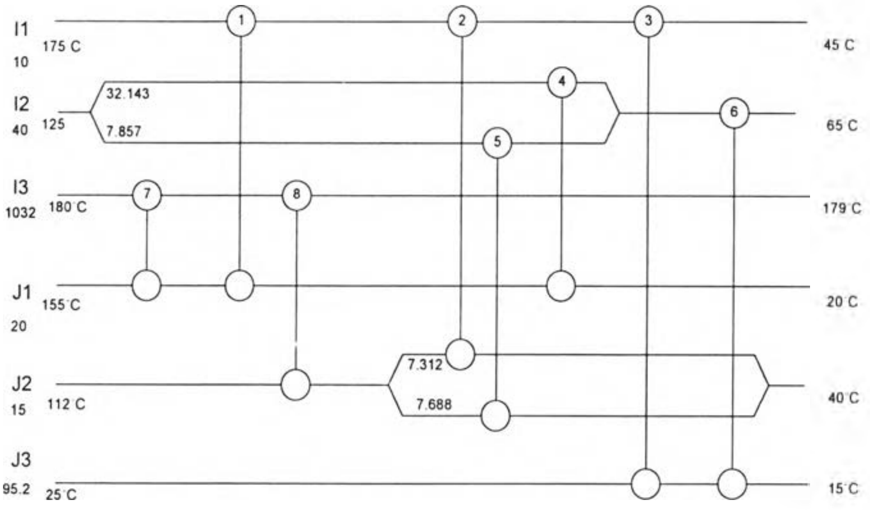


Figure 4.4 Trend of varying the number of temperature intervals for Problem 4.1 (One heat transfer zone).

Table 4.7 Model statistics for Problem 4.1 (One heat transfer zone)

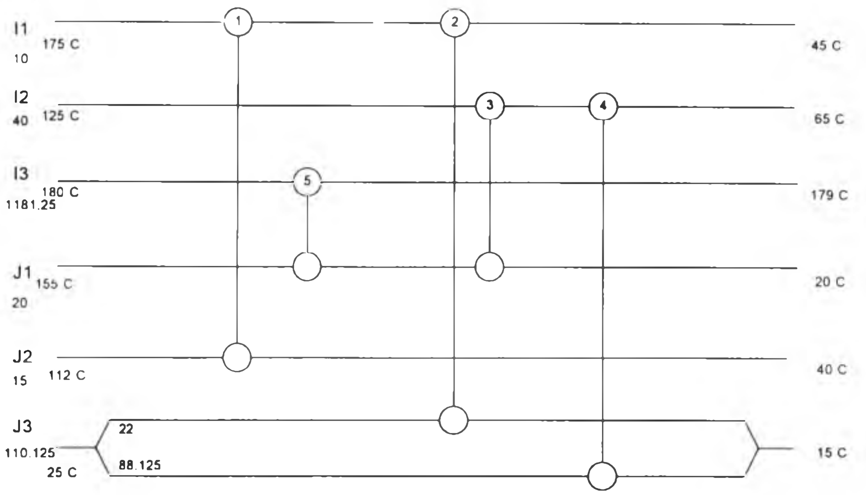
No. of Interval	26	56	112	160	180	192
Single Variables	502	1366	3870	7002	8451	9462
Discrete Variables	82	166	324	451	516	548
Single Equations	1388	3125	6378	8956	10346	11005
Non Zero Elements	4317	11400	29065	48726	58278	64376
Time to reach global optimal solution (sec)	1.531	11.828	95.234	233.281	364.156	247.562
Optimality Gap	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%



No. of heat exchanger	1	2	3	4	5	6	7	8
Heat Load (MJ/hr)	552.143	320.85	427	1542.857	332.143	525	605	427
Area (Prog.), (m^2)	174.233	81.114	97.453	379.039	80.856	101.273	157.24	52.72
Area (Actual), (m^2)	159.421	77.266	91.788	379.039	78.589	106.659	159.563	52.959

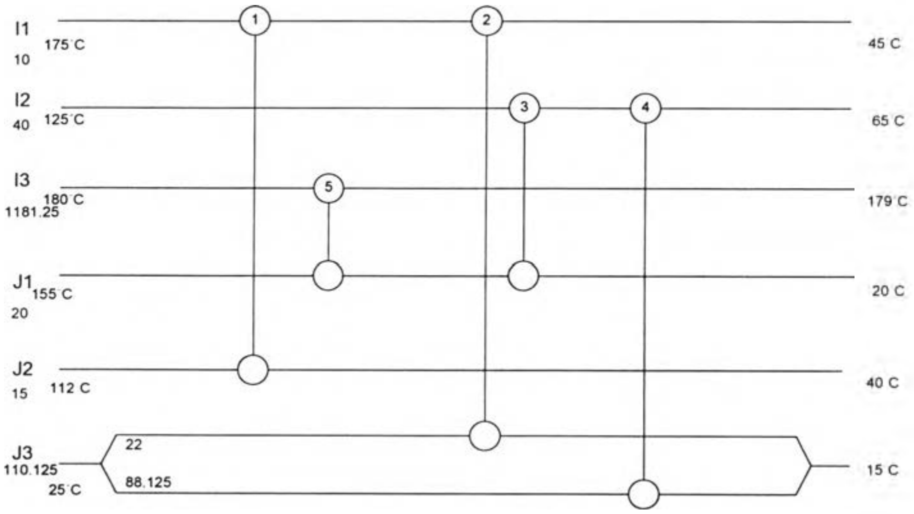
(a) 26 intervals

Figure 4.5 Heat exchanger network for Problem 4.1 with one zone of heat transfer at different number of intervals.



No. of heat exchanger	1	2	3	4	5
Heat Load (MJ/hr)	1080	220	1518.75	881.25	1181.25
Area (Prog.), (m^2)	256.931	61.421	336.991	157.781	244.38
Area (Actual), (m^2)	254.189	61.687	334.29	157.933	244.28

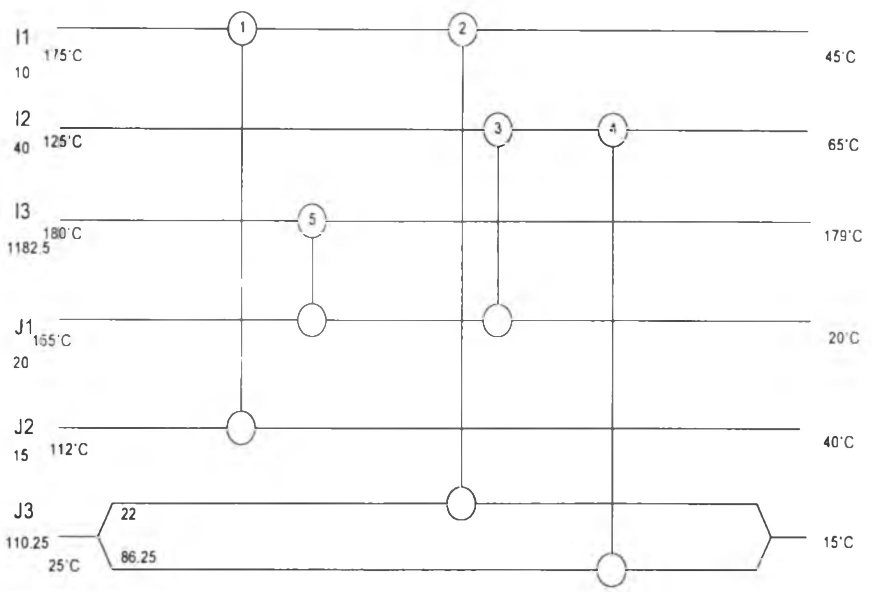
(b) 56 intervals



No. of heat exchanger	1	2	3	4	5
Heat Load (MJ/hr)	1080	220	1518.75	881.25	1181.25
Area (Prog.), (m^2)	254.909	61.629	335.016	157.865	244.307
Area (Actual), (m^2)	254.189	61.687	334.29	157.933	244.28

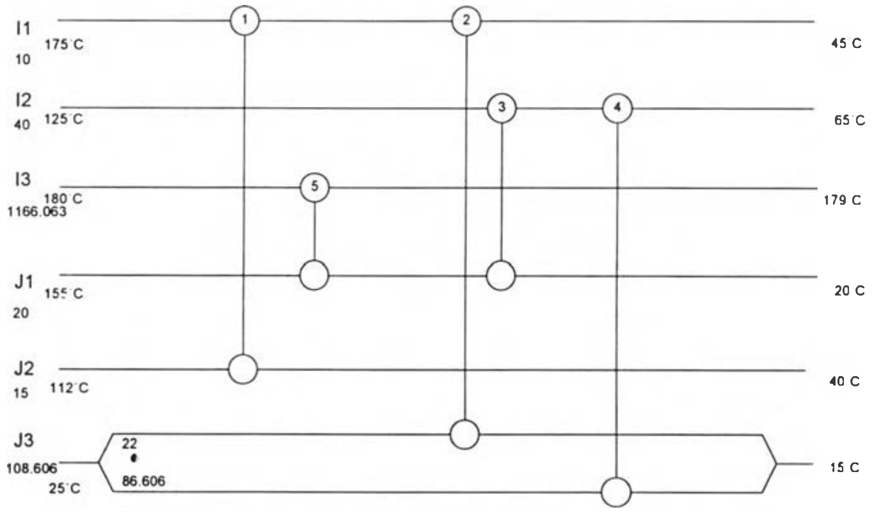
(c) 112 intervals

Figure 4.5 (Cont.) Heat exchanger network for Problem 4.1 with one zone of heat transfer at different number of intervals.



No. of heat exchanger	1	2	3	4	5
Heat Load (MJ/hr)	1080	220	1517.5	882.5	1182.5
Area (Prog.), (m^2)	254.556	61.66	334.285	158.085	244.392
Area (Actual), (m^2)	254.189	61.687	333.618	158.117	244.428

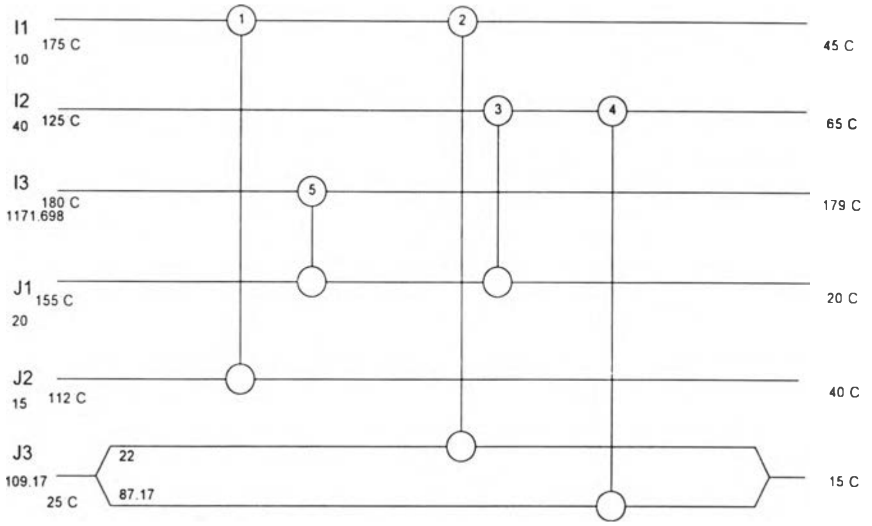
(d) 160 intervals



No. of heat exchanger	1	2	3	4	5
Heat Load (MJ/hr)	1080	220	1533.937	866.063	1166.063
Area (Prog.), (m^2)	254.469	61.664	342.947	155.658	242.473
Area (Actual), (m^2)	254.189	61.687	342.623	155.706	242.471

(e) 180 intervals

Figure 4.5 (Cont.) Heat exchanger network for Problem 4.1 with one zone of heat transfer at different number of intervals.



No. of heat exchanger	1	2	3	4	5
Heat Load (MJ/hr)	1080	220	1528.302	871.698	1171.698
Area (Prog.). (m^2)	254.357	61.699	339.742	156.514	243.147
Area (Actual). (m^2)	254.189	61.687	339.517	156.535	243.149

(f) 192 intervals

Figure 4.5 (Cont.) Heat exchanger network for Problem 4.1 with one zone of heat transfer at different number of intervals.

In conclusion, each solution given from each number of interval is also be optimum even they generate different network and better optimum solution is constructed by the model that generated with one heat transfer zone as indicated in lower total cost.

4.1.2 Problem 4.2 (Problem 7S4, Barbaro's work)

This problem is taken from Papoulias and Grossmann (1983). There are six hot process streams (I1-I6), one cold stream (J1), one heating utility (I7) and one cooling utility (J2).

Table 4.8 Properties of stream for Problem 4.2

Stream	F Ton/hr	Cp KJ/kg-C	Tin C	Tout C	h MJ/h-m^2-C	Q MJ/hr
I1	15	1	675	150	0.2	7875
I2	11	1	590	450	0.2	1540
I3	4.5	1	540	115	0.2	1912.5
I4	60	1	430	345	0.2	5100
I5	12	1	400	100	0.2	3600
I6	125	1	300	230	0.2	8750
I7		1	801	800	0.2	
J1	47	1	60	710	0.2	30550
J2		1	80	140	0.2	

The result structures simulated by MILP model with two heat transfer zones operating are drawn in Figure 4.7. Similarly with the previous example, the exchanger area calculation from programming is closed to the actual value when increasing number of temperature interval. All of the network configurations are consisted of eleven exchanger units with the same amount of hot and cold utility consumption. In contrast, heat exchanger network solutions of Barbaro's work consisted of ten exchangers with the same amount of hot and cold utility. Total cost of Barbaro's solution is lower than cost of the result structures presented in this work because it has lower amount of exchanger unit. However, it has less accuracy of exchanger area calculation for Barbaro's work. Barbaro's solution shown the total exchanger area is 4,711 m^2 whereas the actual exchanger area is required about 5,087 m^2, this is a very big difference. In this work, the solution presents higher accuracy in area calculation. For example, the structure at 144 intervals, area generated by programming is 5,250 m^2 while the actual area is around 5,148 m^2.

Table 4.9 Result of increasing number of temperature intervals for Problem 4.2 (Two heat transfer zones)

No. of Intervals	Total Cost $/yr	Total Area m^2	Hot Utility MJ/hr	Cold Utility MJ/hr	Total Utility MJ/hr	Fixed Cost $/yr	Area Cost $/yr	Utility Cost $/yr
72	674.551.66	5.634.84	8.390.00	6,617.50	15,007.50	58,210.90	438,323.09	178,017.67
99	667.583.04	5,545.26	8.390.00	6.617.50	15,007.50	58,210.90	431,354.45	178,017.67
116	653.621.19	5.365.77	8.390.00	6,617.50	15,007.50	58,210.90	417,392.67	178,017.67
125	651.130.23	5333.75	8.390.00	6,617.50	15,007.50	58,210.90	414.901.75	178,017.67
144	644,576.24	5249.494	8.390.00	6,617.50	15,007.50	58,210.90	408,347.64	178,017.67

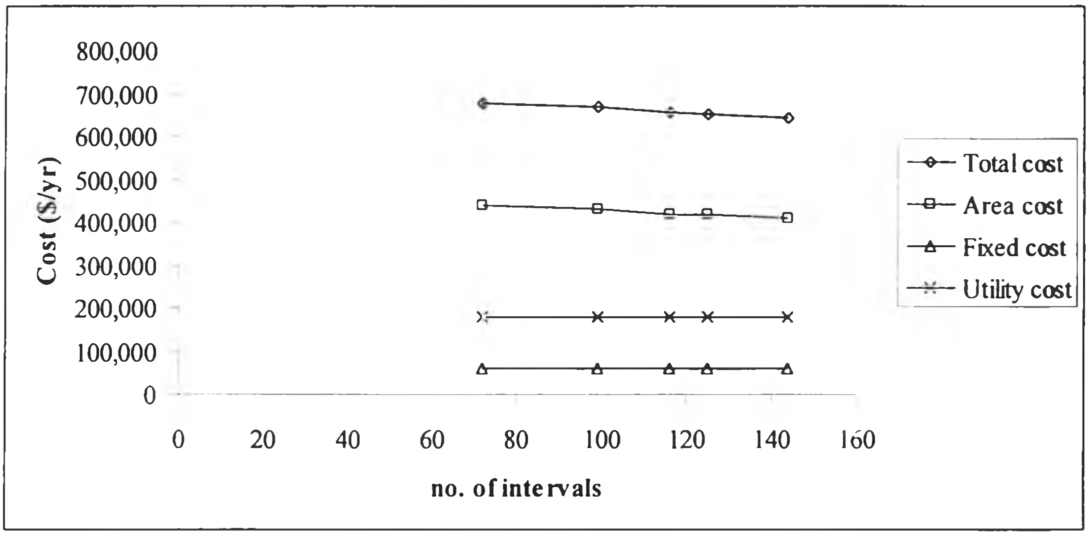
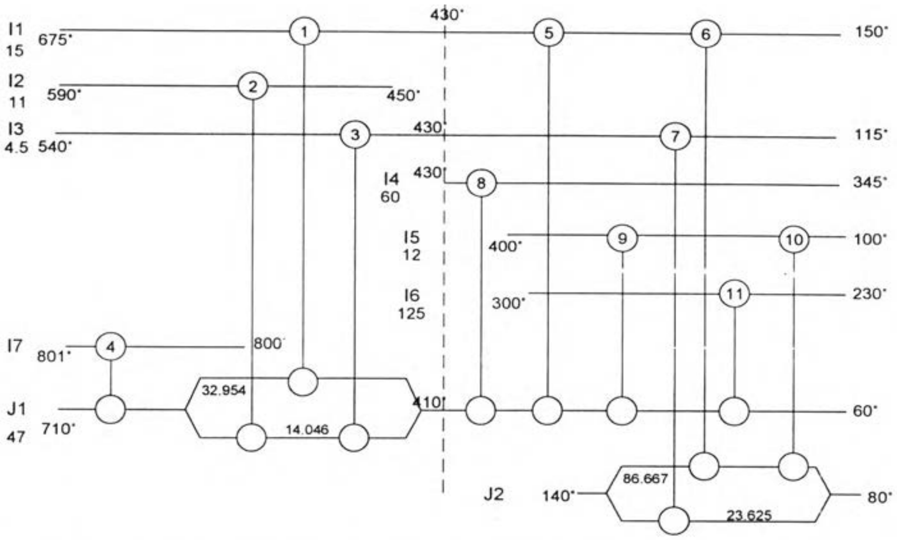


Figure 4.6 Trend of varying the number of temperature intervals for Problem 4.2 (Two heat transfer zones).

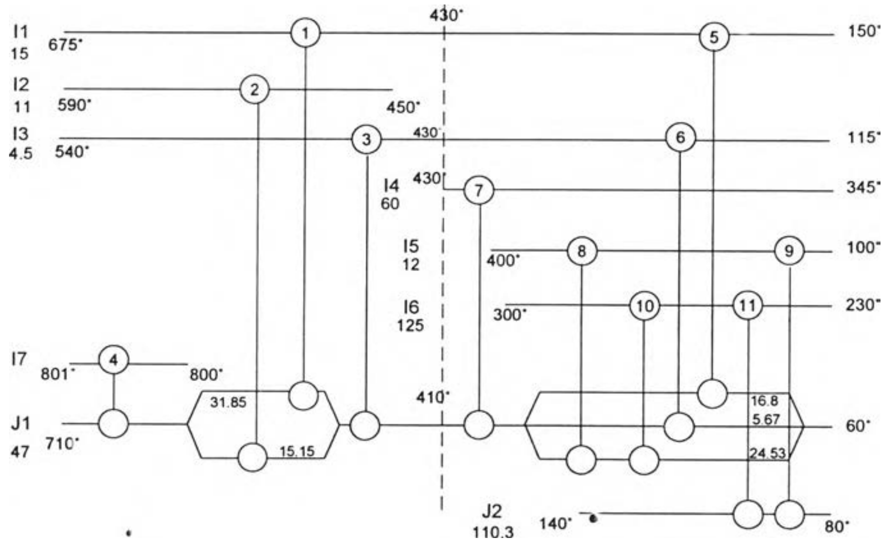
Table 4.10 Model statistics for Problem 4.2 (Two heat transfer zones)

No. of Interval	72	99	116	125	144
Single Variables	1074	1645	2083	2318	2897
Discrete Variables	166	225	262	283	328
Single Equations	2865	4091	4859	5303	6225
Non Zero Elements	9114	13909	17313	19208	23541
Time to reach global optimal solution (sec)	31.671	482.078	2617.86	22409.9	9810.89
Optimality Gap	0.00%	0.00%	0.00%	0.00%	0.00%



No. of heat exchanger	1	2	3	4	5	6	7	8	9	10	11
Heat Load (MJ/hr)	3675	1540	495	8390	1400	2800	1417.5	5100	1200	2400	8750
Area (Prog.), (m^2)	904.125	415.386	115.805	511.747	154.643	276.625	117.543	1791.98	144.786	324.453	877.745
Area (Actual), (m^2)	561.062	1013.74	103	511.42	117.189	278.72	117.543	1686.14	227.279	315.254	866.163

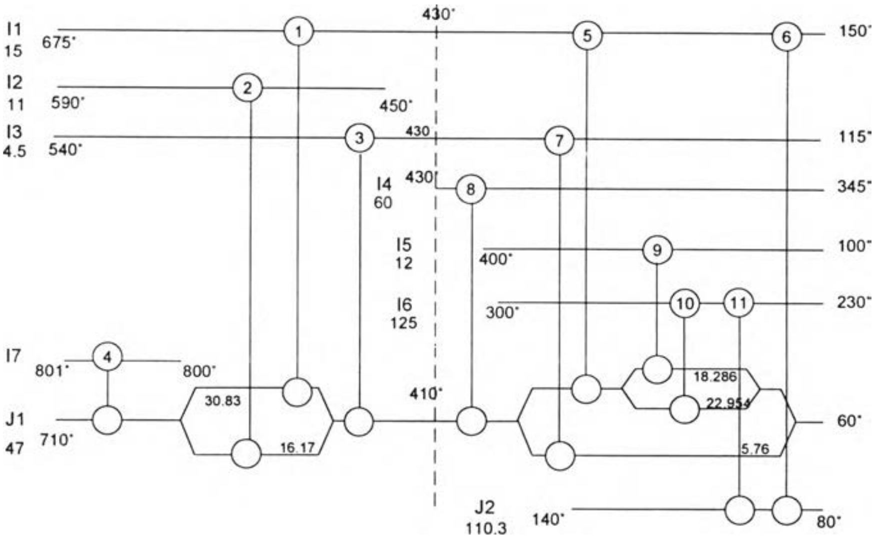
(a) 72 intervals



No. of heat exchanger	1	2	3	4	5	6	7	8	9	10	11
Heat Load (MJ/hr)	3675	1540	495	8390	4200	1417.5	5100	1200	2400	4532.5	4217.5
Area (Prog.), (m^2)	780.759	388.495	114.944	511.312	412.112	178.541	1935.17	158.284	323.024	409.575	333.043
Area (Actual), (m^2)	761.819	334.698	88.9444	511.409	402.755	170.135	1686.1	153.842	308.854	398.387	334.786

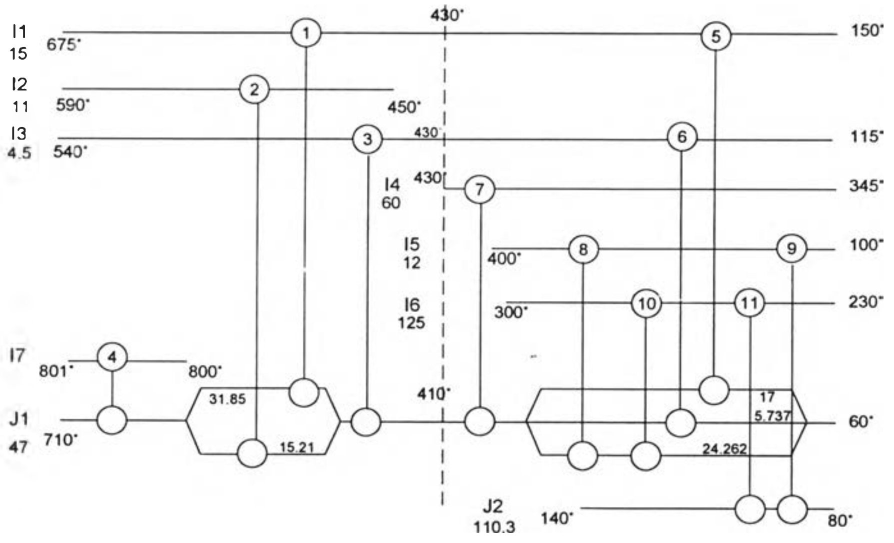
(b) 99 intervals

Figure 4.7 Heat exchanger network for Problem 4.2 with two zones of heat transfer at different number of intervals.



No. of heat exchanger	1	2	3	4	5	6	7	8	9	10	11
Heat Load (MJ/hr)	3675	1540	495	8390	2100	2100	1417.5	5100	3600	4232.5	4517.5
Area (Prog.), (m^2)	660.073	424.656	102.279	511.263	279.131	176.649	181.187	1838.05	467.47	374.722	350.295
Area (Actual), (m^2)	580.318	602.873	99.969	511.418	275.861	174.231	167.077	1685.88	445.025	368.391	328.007

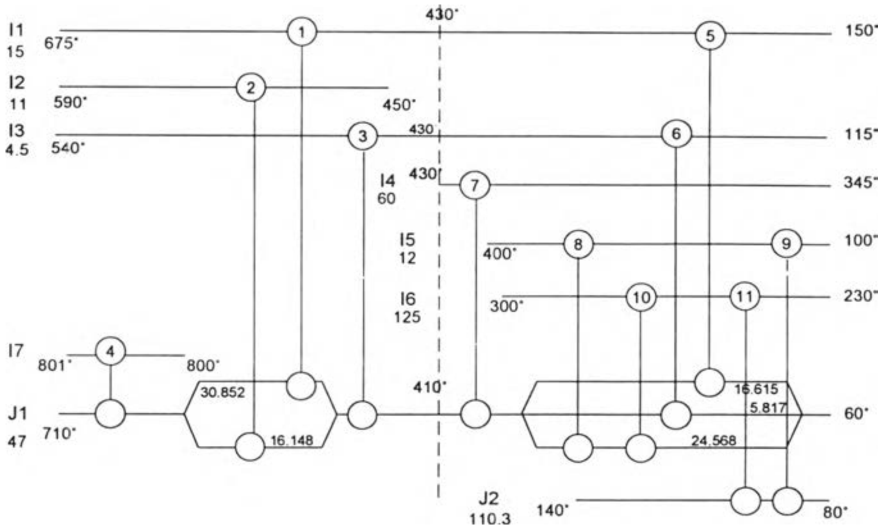
(c) 116 intervals



No. of heat exchanger	1	2	3	4	5	6	7	8	9	10	11
Heat Load (MJ/hr)	3675	1540	495	8390	4200	1417.5	5100	1200	2400	4532.5	4217.5
Area (Prog.), (m^2)	674.492	416.05	99.67	511.383	411.533	173.192	1819.59	164.391	323.024	407.358	333.071
Area (Actual), (m^2)	762.672	333.577	88.944	511.409	397.67	167.838	1686.1	158.599	308.854	404.334	334.786

(d) 125 intervals

Figure 4.7 (Cont.) Heat exchanger network for Problem 4.2 with two zones of heat transfer at different number of intervals.



No. of heat exchanger	1	2	3	4	5	6	7	8	9	10	11
Heat Load (MJ/hr)	3675	1540	495	8390	4200	1417.5	5100	1350	2250	4382.5	4367.5
Area (Prog.), (m^2)	669.105	405.566	97.791	511.353	417.956	173.242	1769.96	182.128	308.699	370.417	343.28
Area (Actual), (m^2)	776.496	318.16	88.944	511.42	407.73	165.261	1686.1	181.915	301.065	367.475	343.206

(e) 144 intervals

Figure 4.7 (Cont.) Heat exchanger network for Problem 4.2 with two zones of heat transfer at different number of intervals.

Table 4.11 depicts the results simulated at one heat transfer zone operating. There is quite a few fluctuation of total cost by changing the number of temperature interval. However, HEN structures at 58, 72, 116, 125 and 169 intervals are almost similar. They have some different flow rate of cold stream, including HEN at 99 intervals, but the matches of hot and cold streams are the same. Fixed charges for all structures are constant. Area and utility costs are the major reasons for total cost variation. In general, heat exchanger area is conflicted with the amount of utility consumption. Tiny utility usage will cause larger exchanger area, because higher amount of heat exchange is required when less utility usage.

Table 4.11 Result of increasing number of temperature intervals for Problem 4.2 (One heat transfer zone)

No. of Intervals	Total Cost $/yr	Total Area m^2	Hot Utility MJ/hr	Cold Utility MJ/hr	Total Utility MJ/hr	Fixed Cost $/yr	Area Cost $/yr	Utility Cost $/yr
58	531.437.89	3,040.31	11.596.40	9.823.90	21.420.29	47.627.10	236.499.71	247,311.11
72	529.816.04	3.018.21	11.600.89	9.828.39	21.429.29	47.627.10	234.780.83	247,408.28
99	528.396.06	3.120.80	11.165.91	9.393.41	20,559.33	47.627.10	242.761.02	238.007.93
116	527.813.26	3.051.27	11.389.23	9.616.73	21.005.97	47.627.10	237,352.11	242.834.11
125	527.914.03	3.115.75	11.161.81	9.389.31	20.551.11	47.627.10	242.367.65	237.919.19
144	527,505.22	3.078.95	11.275.36	9,502.86	20,778.21	47,627.10	239,505.05	240,373.12
169	527,647.77	3,054.64	11.369.46	9.596.96	20,966.42	47,627.10	237,613.95	242,406.76

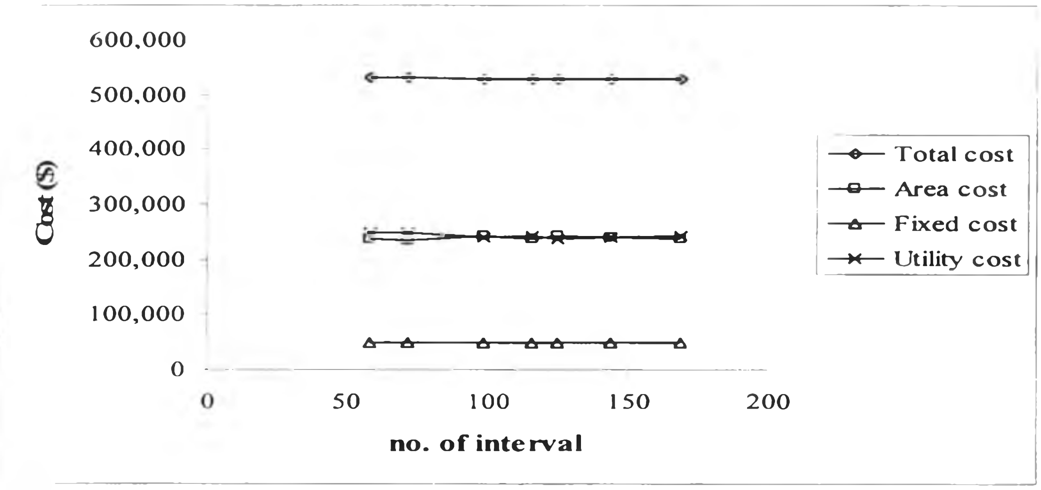
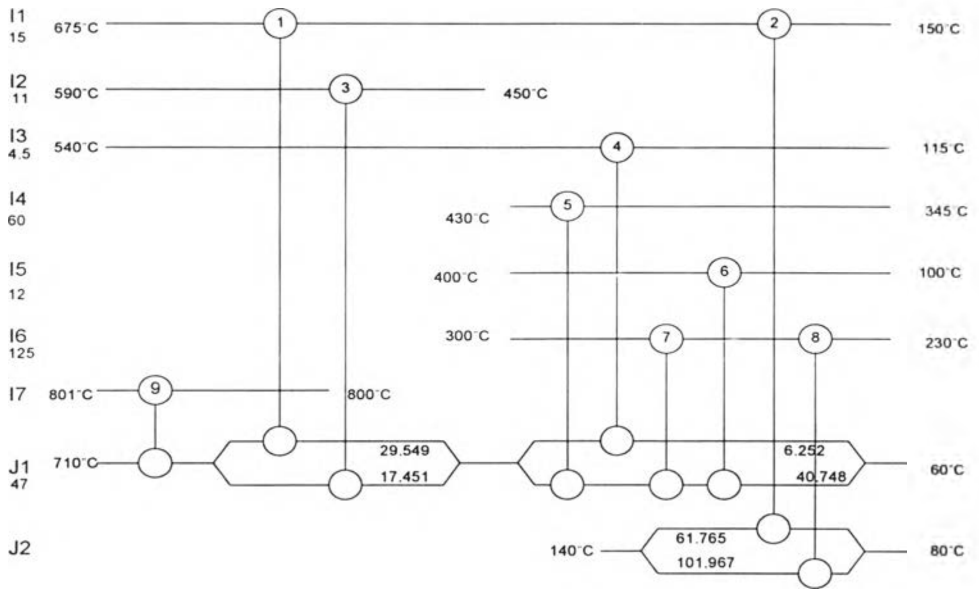


Figure 4.8 Trend of varying the number of temperature intervals for Problem 4 2 (One heat transfer zone).

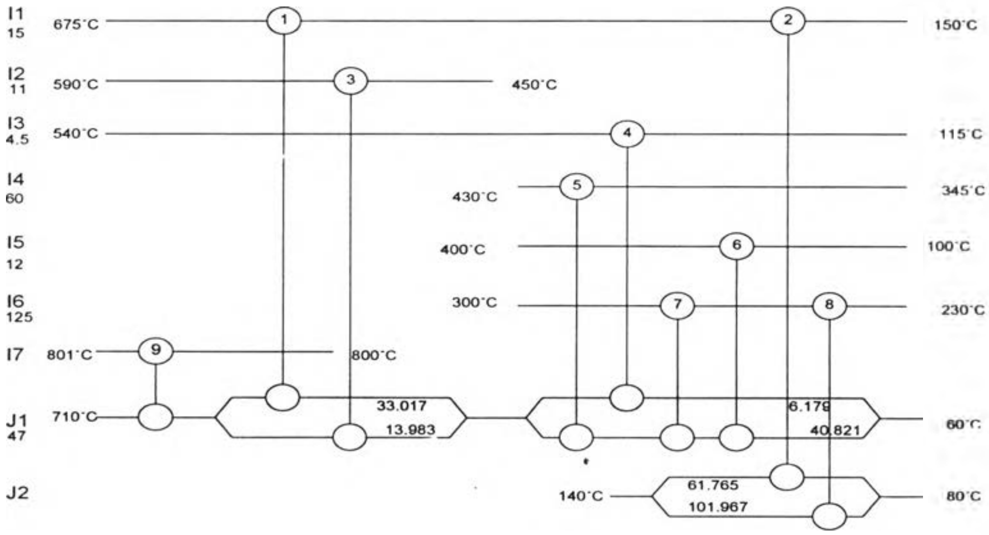
Table 4.12 Model statistics for Problem 4.2 (One heat transfer zones)

No. of Interval	58	72	99	116	125	144	169
Single Variables	1257	1703	2579	3350	3747	4725	5166
Discrete Variables	180	223	296	352	380	439	470
Single Equations	3170	4043	5511	6682	7250	8435	9124
Non Zero Elements	10584	14173	20796	26551	29419	36128	39476
Time to reach global optimal solution (sec)	342.187	315.015	750.89	9053.844	33315.39	115509	15442.6
Optimality Gap	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%



No. of heat exchanger	1	2	3	4	5	6	7	8	9
Heat Load (MJ/hr)	4169.118	3705.882	1540	1912.5	5100	3600	2631.985	6118.015	11596.4
Area (Prog.), (m^2)	356.315	271.618	128.785	206.47	476.122	323.333	243.589	417.2	616.879
Area (Actual), (m^2)	379.610	257.707	116.320	185.035	460.416	312.827	245.159	423.687	617.477

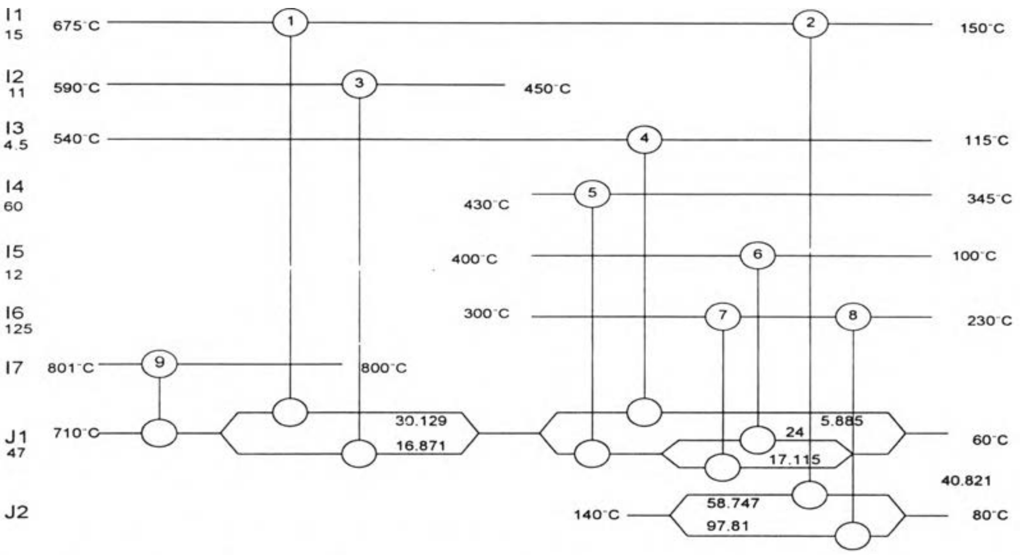
(a) 58 intervals



No. of heat exchanger	1	2	3	4	5	6	7	8	9
Heat Load (MJ/hr)	4500	3375	1540	1912.5	5100	3600	2296.607	6453.393	11600.89
Area (Prog.), (m^2)	406.704	250.719	137.566	200.454	432.517	321.862	208.162	442.514	617.716
Area (Actual), (m^2)	445.635	247.723	118.743	187.356	426.888	312.698	202.447	442.696	617.605

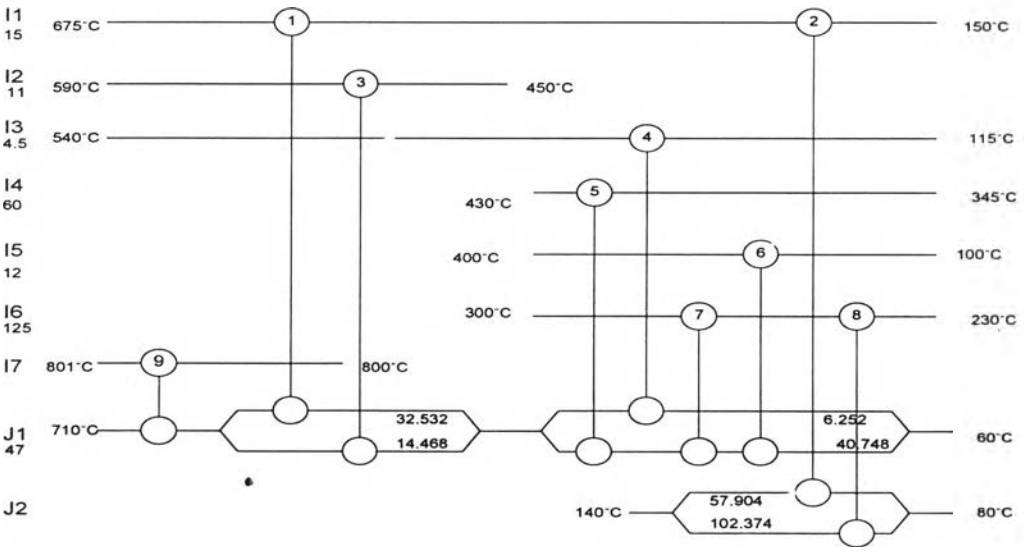
(b) 72 intervals

Figure 4.9 Heat exchanger network for Problem 4.2 with one zone of heat transfer at different number of intervals.



No. of heat exchanger	1	2	3	4	5	6	7	8	9
Heat Load (MJ/hr)	4350.192	3524.808	1540	1912.5	5100	3600	2881.394	5868.606	11165.91
Area (Prog.), (m^2)	418.103	254.357	148.825	203.902	484.233	373.955	223.788	409.259	604.381
Area (Actual), (m^2)	471.2803	252.3347	122.5235	198.1376	478.1918	373.9547	219.6986	409.3157	604.5472

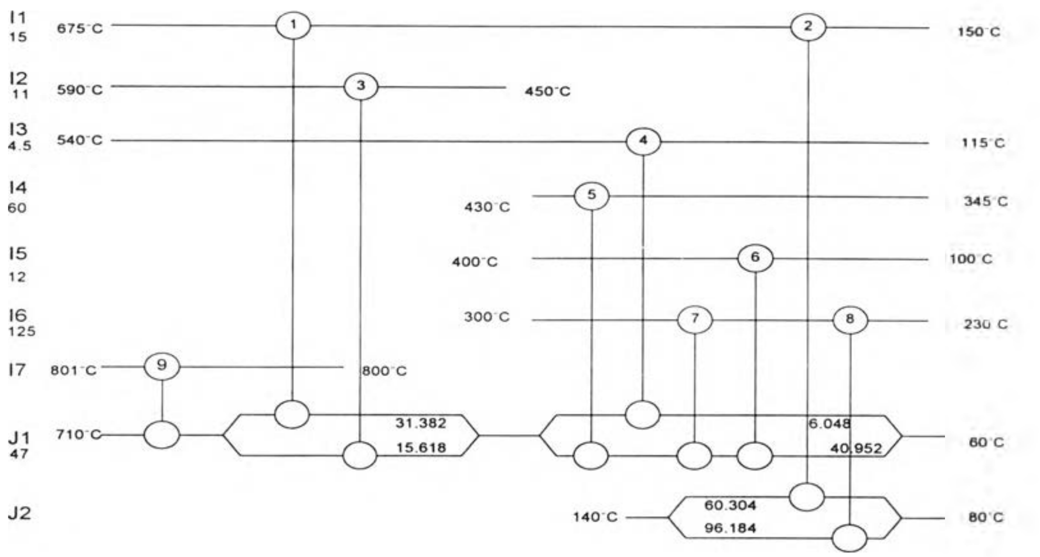
(c) 99 intervals



No. of heat exchanger	1	2	3	4	5	6	7	8	9
Heat Load (MJ/hr)	4400.735	3474.265	1540	1912.5	5100	3600	2607.531	6142.469	11389.23
Area (Prog.), (m^2)	412.732	252.873	138.868	189.171	461.999	317.382	241.565	425.515	611.164
Area (Actual), (m^2)	443.4396	250.7963	123.4483	185.035	457.9089	312.8266	241.9069	425.0785	611.2953

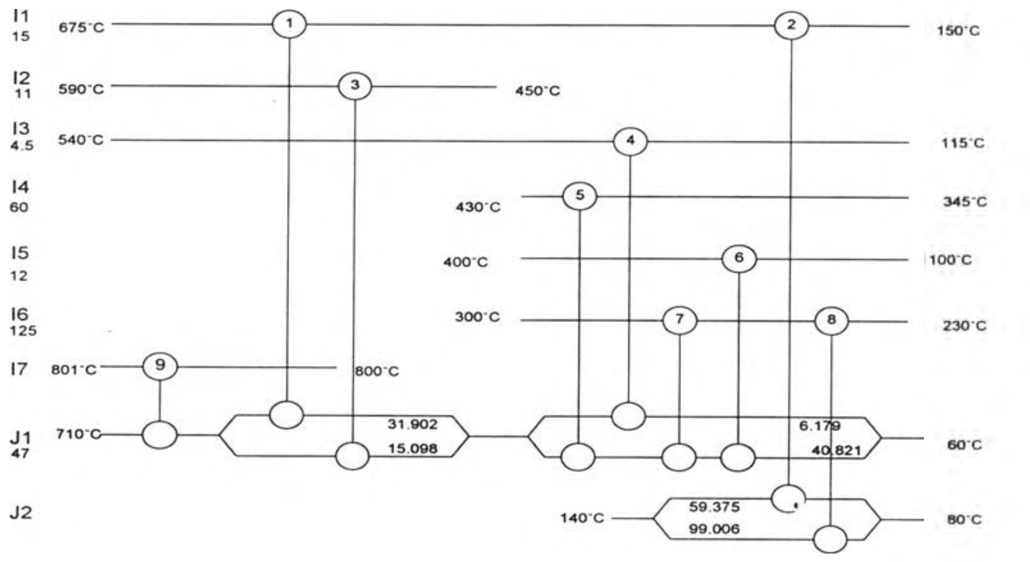
(d) 116 intervals

Figure 4.9 (Cont.) Heat exchanger network for Problem 4.2 with one zone of heat transfer at different number of intervals.



No. of heat exchanger	1	2	3	4	5	6	7	8	9
Heat Load (MJ/hr)	4256.757	3618.243	1540	1912.5	5100	3600	2978.936	5771.064	11161.81
Area (Prog.), (m^2)	399.56	257.33	148.171	195.645	496.715	315.728	294.457	403.843	604.297
Area (Actual), (m^2)	433.7069	255.1326	127.9775	191.8462	493.5911	312.4741	292.4674	403.6456	604.4174

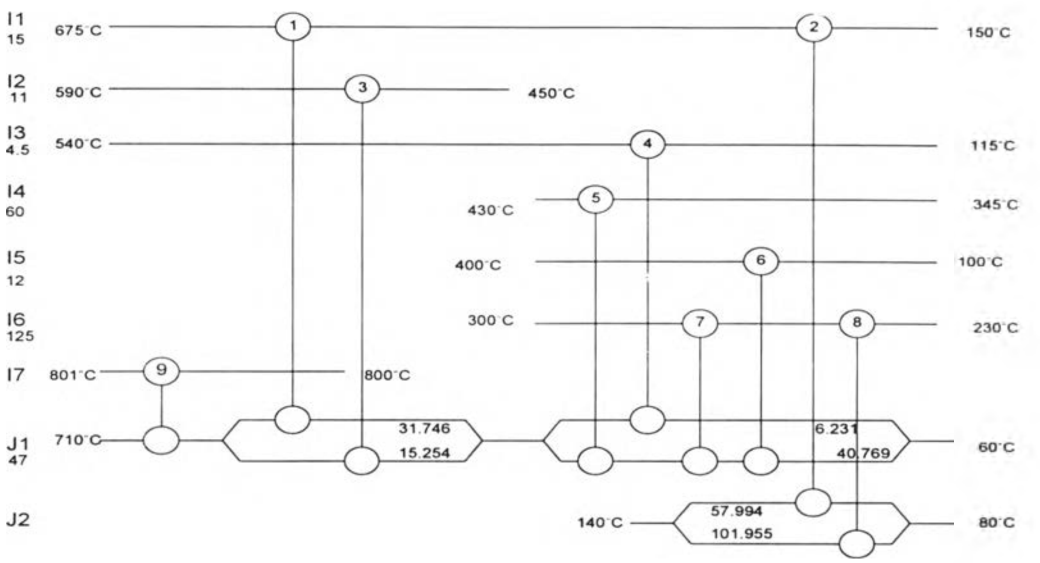
(e) 125 intervals



No. of heat exchanger	1	2	3	4	5	6	7	8	9
Heat Load (MJ/hr)	4312.5	3562.5	1540	1912.5	5100	3600	2809.643	5940.357	11275.36
Area (Prog.), (m^2)	404.062	254.388	143.208	190.171	479.62	316.362	269.812	413.541	607.782
Area (Actual), (m^2)	434.1184	253.4724	125.7772	187.353	477.6528	312.6983	269	413.4733	607.8651

(f) 144 intervals

Figure 4.9 (Cont.) Heat exchanger network for Problem 4.2 with one zone of heat transfer at different number of intervals.



No. of heat exchanger	1	2	3	4	5	6	7	8	9
Heat Load (MJ/hr)	4395.349	3479.651	1540	1912.5	5100	3600	2632.692	6117.308	11369.46
Area (Prog.), (m^2)	415.093	252.314	137.302	187.047	462.113	318.946	247.497	423.762	610.561
Area (Actual), (m^2)	448.9154	250.9624	121.5403	185.69	460.0116	312.7881	245.0982	423.638	610.701

(g) 169 intervals

Figure 4.9 (Cont.) Heat exchanger network for Problem 4.2 with one zone of heat transfer at different number of intervals.

All other problems will be presented as follows in the same way as previous one. The heat exchanger networks constructed by simulating the MILP model are also illustrated in term of difference in number of interval.

4.1.3 Problem 4.3 (Problem 10SP1, Barbaro's work)

Table 4.13 Properties of stream for Problem 4.3

Stream	F Ton/hr	Cp KJ/kg-C	Tin C	Tout C	h MJ/h-m^2-C	Q MJ/hr
I1	8.79	1	160	93	0.2	588.93
I2	10.54	1	249	138	0.2	1169.94
I3	14.77	1	227	66	0.2	2377.97
I4	12.56	1	271	149	0.2	1532.32
I5	17.73	1	199	66	0.2	2358.09
J1	7.62	1	60	160	0.2	762
J2	6.08	1	116	222	0.2	644.48
J3	8.44	1	38	221	0.2	1544.52
J4	17.28	1	82	177	0.2	1641.6
J5	13.9	1	93	205	0.2	1556.8
J6		1	38	82	0.2	

Table 4.14 Result of increasing number of temperature intervals for Problem 4.3 (One heat transfer zone)

No. of Intervals	Total Cost $/yr	Total Area m^2	Hot Utility MJ/hr	Cold Utility MJ/hr	Total Utility MJ/hr	Fixed Cost $/yr	Area Cost $/yr	Utility Cost $/yr
42	234,563.27	2,222.17	0	1,877.85	1,877.85	58,210.90	172,857.77	3,494.68
55	224,862.29	2,097.45	0	1,877.85	1,877.85	58,210.90	163,156.75	3,494.68
65	222,227.86	2,063.59	0	1,877.85	1,877.85	58,210.90	160,522.31	3,494.68
85	219,242.05	2,093.23	0	1,877.85	1,877.85	52,919.00	162,828.41	3,494.68
105	217,995.70	2,077.21	0	1,877.85	1,877.85	52,919.00	161,582.09	3,494.68

Table 4.15 Model statistics for Problem 4.3

No. of Interval	41	55	65	85	105
Single Variables	1447	2029	2504	3568	4740
Discrete Variables	260	332	387	502	613
Single Equations	3973	5447	6586	8950	11235
Non Zero Elements	11886	17032	21255	30378	39916
Time to reach global optimal solution (sec)	161.906	480.171	4172.94	35983	117958
Optimality Gap	0.00%	0.00%	0.00%	0.00%	0.00%

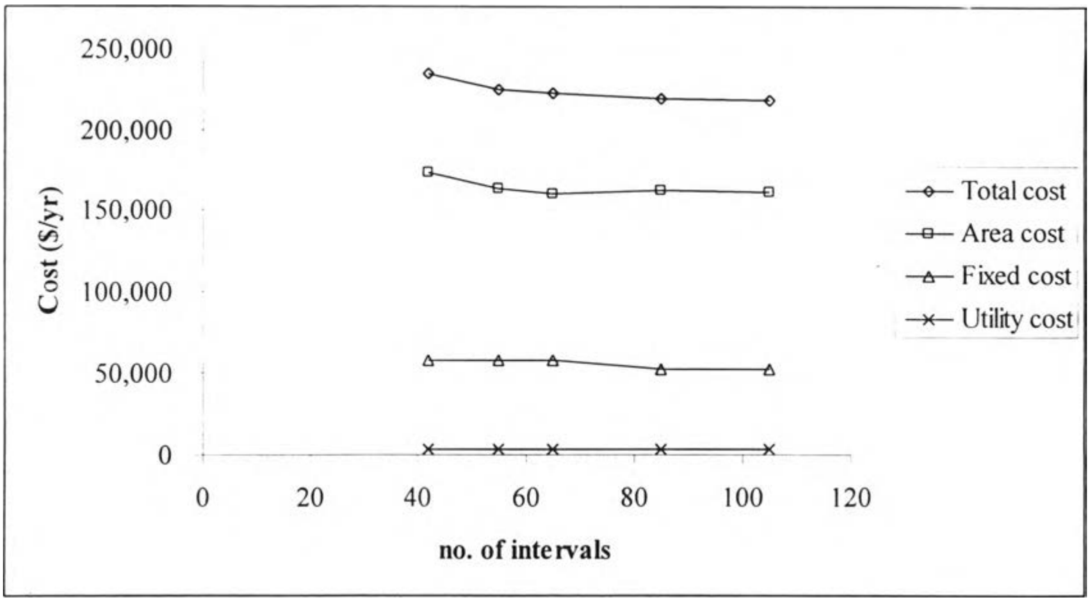
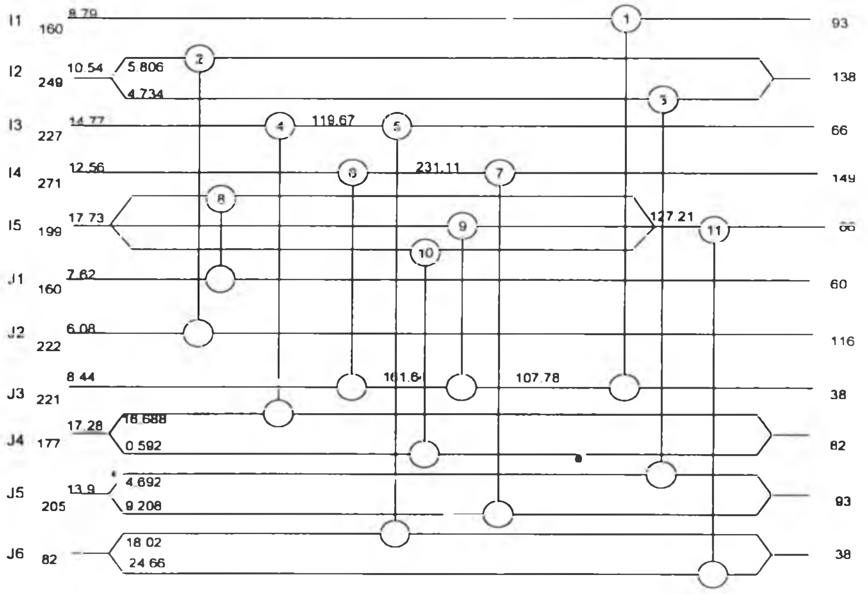


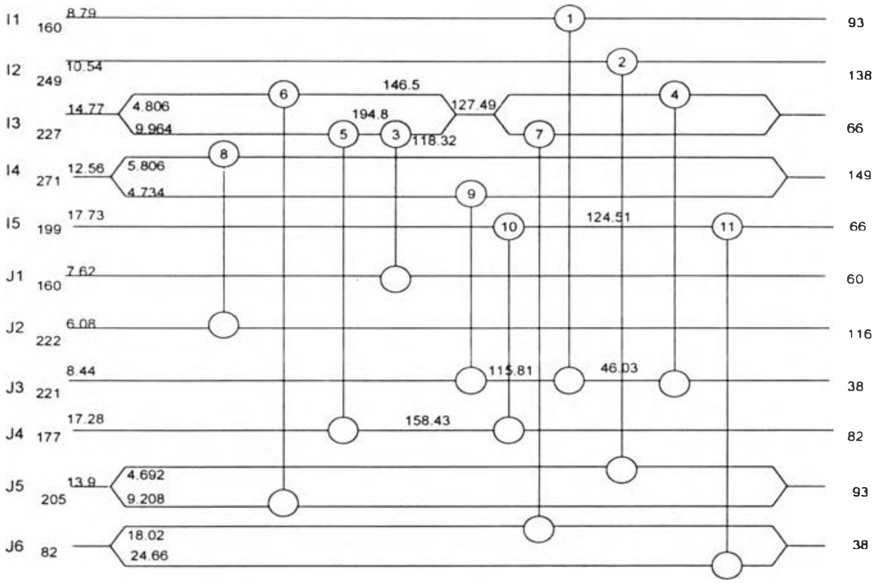
Figure 4.10 Trend of varying the number of temperature intervals for Problem 4.3.



No. of heat exchanger	1	2	3	4	5	6	7	8	9	10	11
Heat Load (MJ/hr)	588.93	644.48	525.46	1585.31	792.657	500.98	1031.34	762	454.61	56.287	1085.19
Area (Prog.), (m^2)	132.54	263.972	118.086	414.411	257.812	83.843	265.512	177.268	135.222	18.876	354.623
Area (Actual), (m^2)	109.879	263.972	118.086	364.068	243.174	84.6216	263.281	147.014	165.765	17.4675	302.11

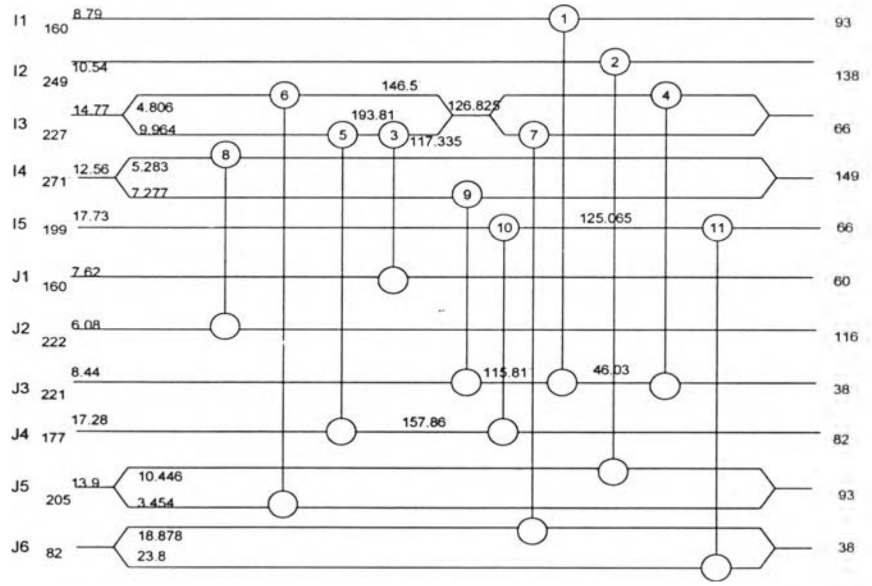
(a) 42 intervals

Figure 4.11 Heat exchanger network for Problem 4.3.



No. of heat exchanger	1	2	3	4	5	6	7	8	9	10	11
Heat Load (MJ/hr)	588.93	1169.94	762	67.75	320.85	386.86	840.51	644.48	887.84	1320.75	1037.34
Area (Prog.), (m^2)	141.142	262.919	176.606	21.223	74.507	125.799	242.646	159.232	239.657	342.777	310.946
Area (Actual), (m^2)	129.248	262.919	167.280	13.534	74.923	109.136	233.213	159.232	216.427	318.004	298.501

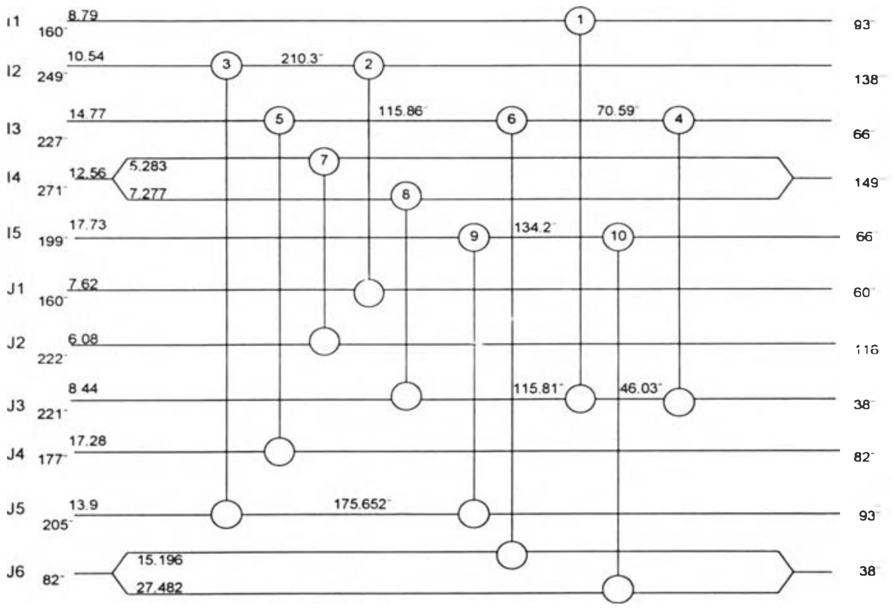
(b) 55 intervals



No. of heat exchanger	1	2	3	4	5	6	7	8	9	10	11
Heat Load (MJ/hr)	588.93	1169.94	762	67.75	330.729	386.86	830.631	644.48	887.84	1310.87	1047.22
Area (Prog.), (m^2)	138.47	262.919	178.473	21.615	81.247	118.75	232.526	159.232	233.174	332.809	304.372
Area (Actual), (m^2)	129.248	262.919	171.075	13.5989	77.655	109.136	232.311	159.232	216.427	311.407	299.259

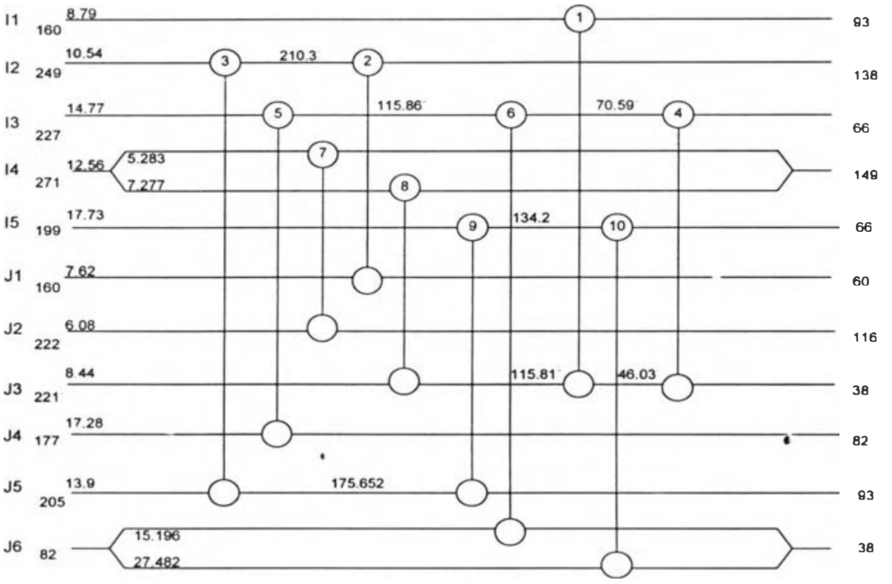
(c) 65 intervals

Figure 4.11 (Cont.) Heat exchanger network for Problem 4.3.



No. of heat exchanger	1	2	3	4	5	6	7	8	9	10
Heat Load (MJ/hr)	588.93	762	407.94	67.75	1641.6	668.62	644.48	887.84	1148.86	1209.23
Area (Prog.), (m^2)	133.973	121.225	107.496	25.469	415.066	210.02	159.232	221.335	387.791	311.626
Area (Actual), (m^2)	129.248	120.683	104.231	25.817	396.454	201.265	159.232	216.427	365.488	311.241

(d) 85 intervals



No. of heat exchanger	1	2	3	4	5	6	7	8	9	10
Heat Load (MJ/hr)	588.93	762	407.94	67.75	1641.6	668.62	644.48	887.84	1148.86	1209.23
Area (Prog.), (m^2)	131.897	120.762	105.584	25.2	405.15	209.028	159.232	220.157	384.439	315.762
Area (Actual), (m^2)	129.248	120.683	104.231	25.817	396.454	201.265	159.232	216.427	365.488	311.241

(e) 105 intervals

Figure 4.11 (Cont.) Heat exchanger network for Problem 4.3.

4.1.4 Problem 4.4 (Problem EX1, Barbaro's work)

Table 4.16 Properties of stream for Problem 4.4

Stream	F	Cp	Tin	Tout	h	Q
	Ton/hr	KJ/kg-C	C	C	MJ/h-m^2-C	MJ/hr
I1	228.5	1	159	77	0.4	18737
I2	20.4	1	267	88	0.3	3651.6
I3	53.8	1	343	90	0.25	13611.4
I4		1	376	375.9	1	
J1	93.3	1	26	127	0.15	9423.3
J2	196.1	1	118	265	0.5	28826.7
J3		1	15	30	0.6	

Table 4.17 Result of increasing number of temperature intervals for Problem 4.4 (Two heat transfer zones)

No. of Intervals	Total Cost	Total Area	Hot Utility	Cold Utility	Total Utility	Fixed Cost	Area Cost	Utility Cost
	\$/yr	m^2	MJ/hr	MJ/hr	MJ/hr	\$/yr	\$/yr	\$/yr
67	768,666.81	7,601.87	10,645.20	8,395.20	19,040.40	73,385.10	469,415.47	225,866.17
134	735,493.66	7,064.65	10,645.20	8,395.20	19,040.40	73,385.10	436,242.38	225,866.17
165	732,867.58	7,022.13	10,645.20	8,395.20	19,040.40	73,385.10	433,616.34	225,866.17
207	729,766.45	6,971.91	10,645.20	8,395.20	19,040.40	73,385.10	430,515.13	225,866.17
236	730,093.91	6,977.21	10,645.20	8,395.20	19,040.40	73,385.10	430,842.66	225,866.17

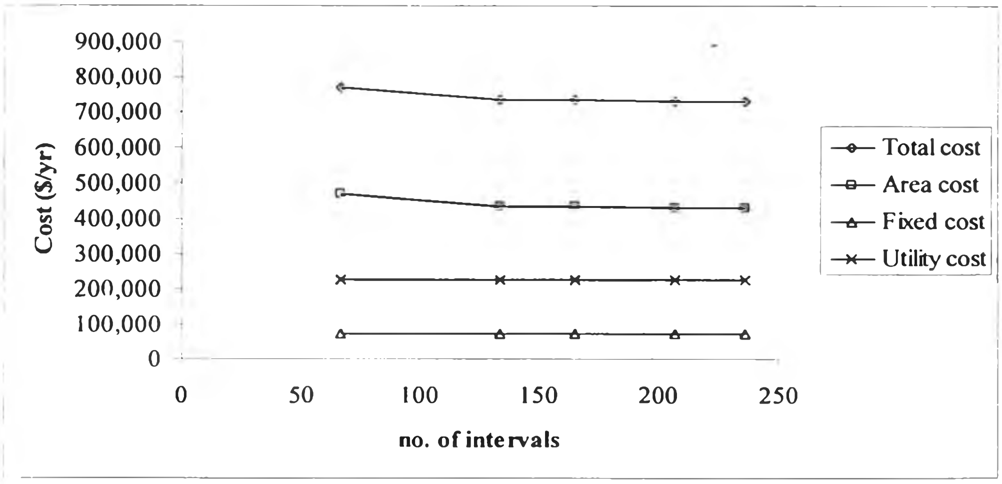
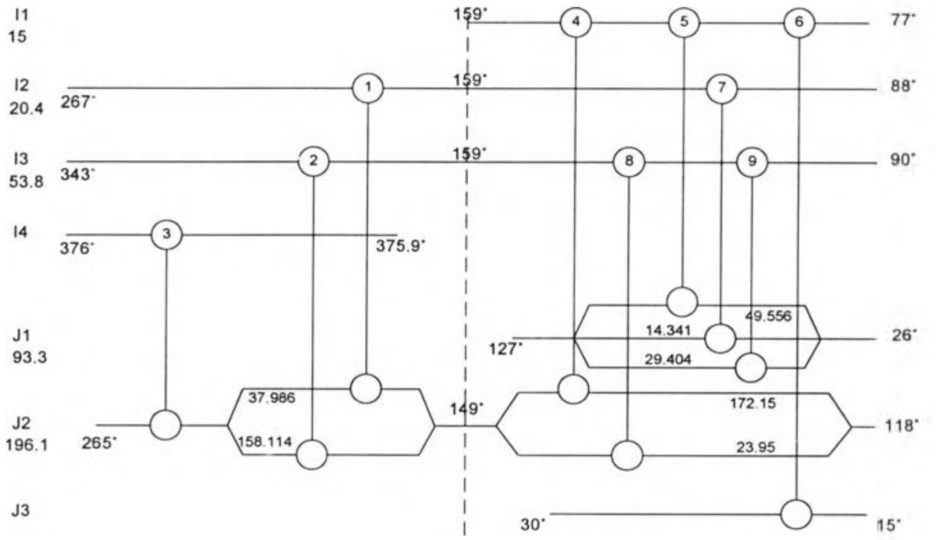


Figure 4.12 Trend of varying the number of temperature intervals for Problem 4.4 (Two heat transfer zone).

Table 4.18 Model statistics for Problem 4.4 (Two heat transfer zones)

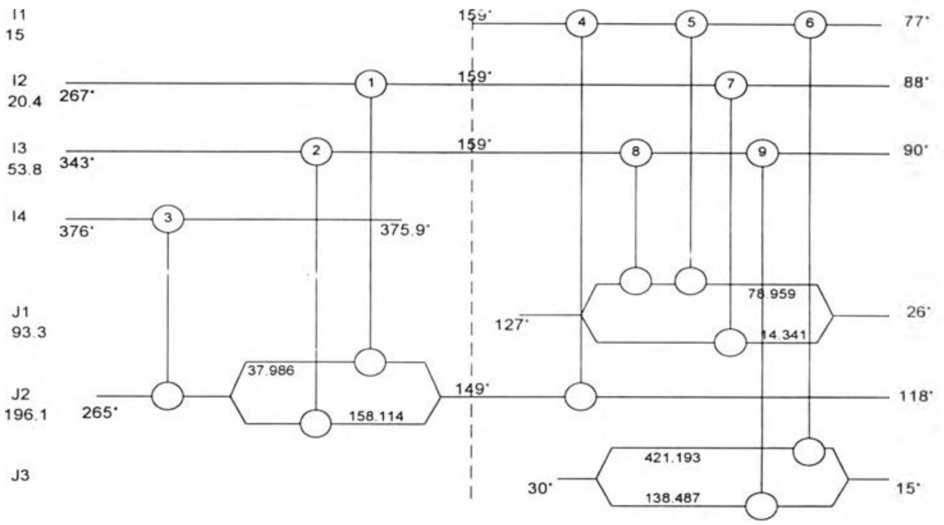
No. of Interval	67	134	165	207	236
Single Variables	984	2516	3927	6063	6255
Discrete Variables	153	297	370	467	500
Single Equations	2696	5662	7180	9200	9844
Non Zero Elements	8613	21159	30955	45219	47290
Time to reach global optimal solution (sec)	2.218	69.5	1333.73	2462.25	2227.56
Optimality Gap	0.00%	0.00%	0.00%	0.00%	0.00%



No. of heat exchanger	1	2	3	4	5	6	7	8	9
Heat Load (MJ/hr)	2,203.200	9,899.200	10,645.200	5,336.660	5,005.140	8,395.200	1,448.400	742.440	2,969.760
Area (Prog.), (m^2)	597.945	1,486.448	233.644	1,911.310	1,385.109	489.469	329.553	268.314	900.078
Area (Actual), (m^2)	421.078	1,257.699	234.538	1,785.884	1,345.619	483.642	319.323	258.637	869.720

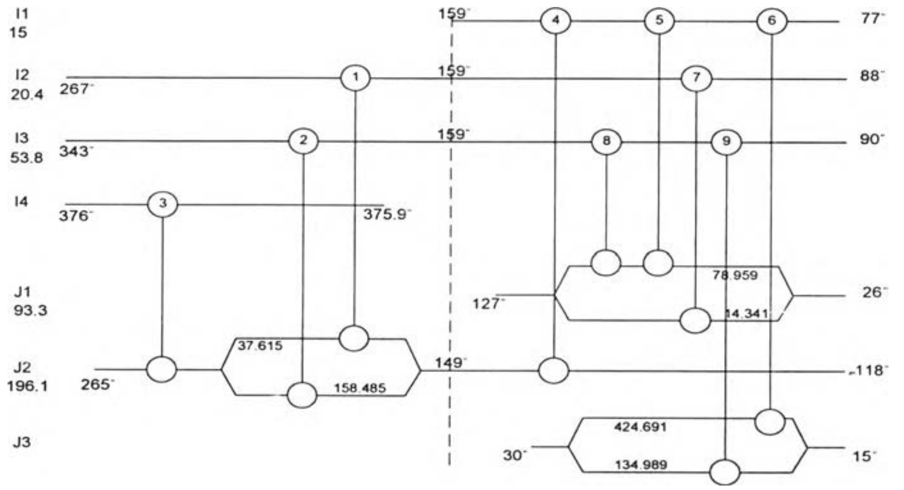
(a) 67 intervals

Figure 4.13 Heat exchanger network for Problem 4.4 with two zones of heat transfer at different number of intervals.



No. of heat exchanger	1	2	3	4	5	6	7	8	9
Heat Load (MJ/hr)	2,203.200	9,899.200	10,645.200	6,079.100	6,340.000	6,317.900	1,448.400	1,634.900	2,077.300
Area (Prog.), (m^2)	448.658	1,328.122	234.060	2,321.082	1,238.000	385.291	321.701	649.157	138.583
Area (Actual), (m^2)	421.078	1,257.699	234.538	2,269.685	1,220.920	386.391	319.323	649.079	136.430

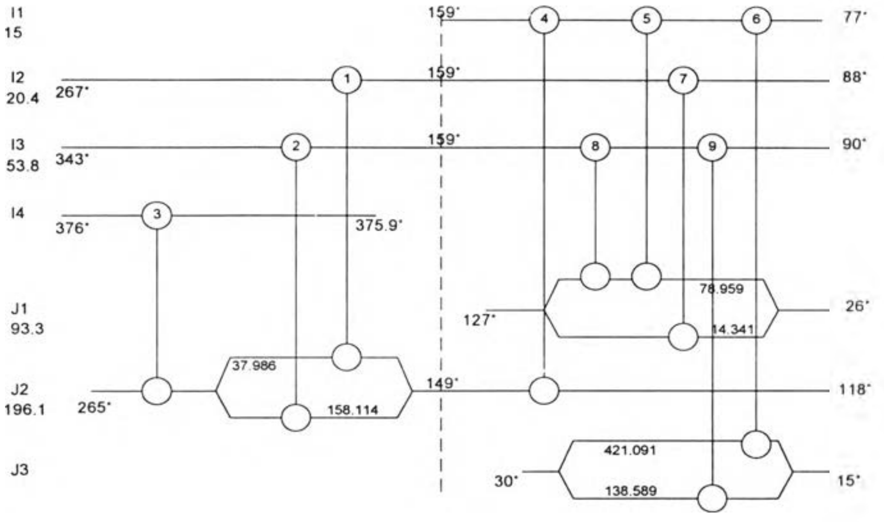
(b) 134 intervals



No. of heat exchanger	1	2	3	4	5	6	7	8	9
Heat Load (MJ/hr)	2,203.200	9,899.200	10,645.200	6,079.100	6,287.536	6,370.364	1,448.400	1,687.364	2,024.836
Area (Prog.), (m^2)	447.637	1,318.728	234.237	2,300.777	1,200.201	388.884	320.029	677.912	133.722
Area (Actual), (m^2)	423.664	1,256.710	234.535	2,269.685	1,196 308	388.982	319.323	674.250	133.673

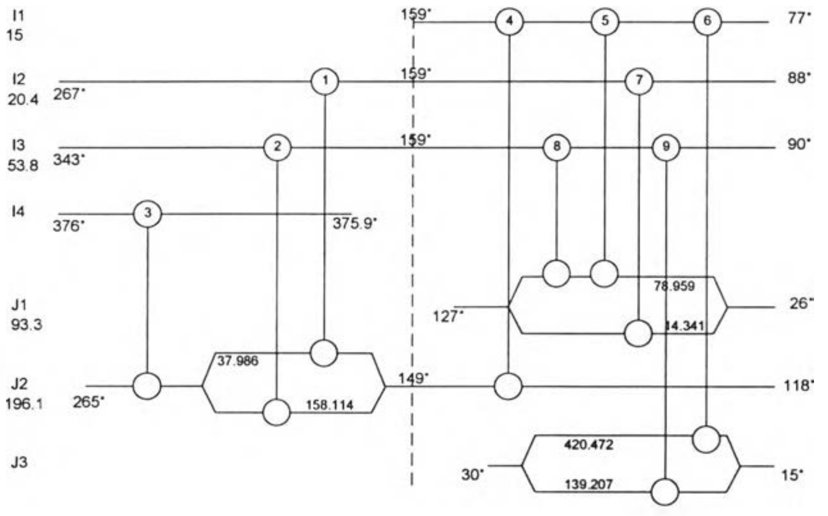
(c) 165 intervals

Figure 4.13 (Cont.) Heat exchanger network for Problem 4.4 with two zones of heat transfer at different number of intervals.



No. of heat exchanger	1	2	3	4	5	6	7	8	9
Heat Load (MJ/hr)	2,203.200	9,899.200	10,645.200	6,079 100	6,341.532	6,316.368	1,448.400	1,633.368	2,078.832
Area (Prog.), (m^2)	435.303	1,299.508	234.159	2,287.322	1,224.751	386.216	319.718	648.386	136.542
Area (Actual), (m^2)	421.078	1,257.699	234.538	2,269.685	1,221.644	386.316	319.323	648.321	136.509

(d) 207 intervals



No. of heat exchanger	1	2	3	4	5	6	7	8	9
Heat Load (MJ/hr)	2,203.200	9,899.200	10,645.200	6,079.100	6,350.812	6,307.087	1,448.400	1,624.087	2,088.112
Area (Prog.), (m^2)	436.254	1,305.810	234.159	2,283.719	1,228.564	385.804	319.756	646.106	137.037
Area (Actual), (m^2)	421.078	1,257.699	234.538	2,269.685	1,226.074	385.855	319.323	643.892	136.992

(e) 236 intervals

Figure 4.13 (Cont.) Heat exchanger network for Problem 4.4 with two zones of heat transfer at different number of intervals.

Table 4.19 Result of increasing number of temperature intervals for Problem 4.4 (One heat transfer zone)

No. of Intervals	Total Cost $/yr	Total Area m^2	Hot Utility MJ/hr	Cold Utility MJ/hr	Total Utility MJ/hr	Fixed Cost $/yr	Area Cost $/yr	Utility Cost $/yr
67	632.198.30	4,178.47	14.489.55	12,239.55	26,729.11	65,231.20	258,020.58	308.946.50
134	622.685.62	3,844.32	15,381.46	13,131.46	28.512.92	57,077.30	237,386.76	328,221.48
165	622.374.70	3,831.83	15.402.76	13.151.76	28,554.51	57,077.30	236.615.63	328.679.87
207	622.047.35	3,841.50	15.359.98	13.109.98	28.469.96	57,077.30	237.212.87	327,757.28
236	621.871.52	3.869.13	15,272.90	13.022.90	28,295.79	57,077.30	238.918.96	325.875.31

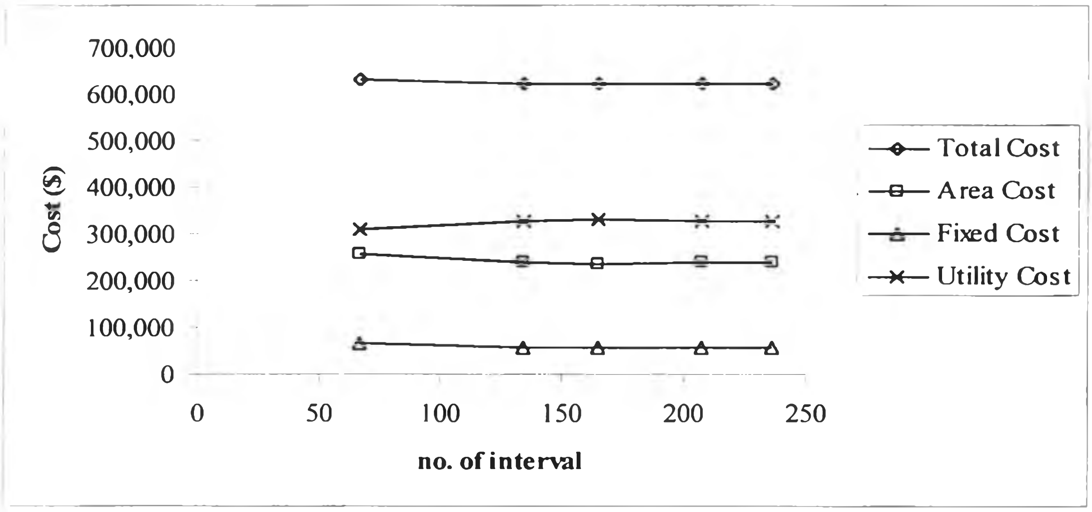
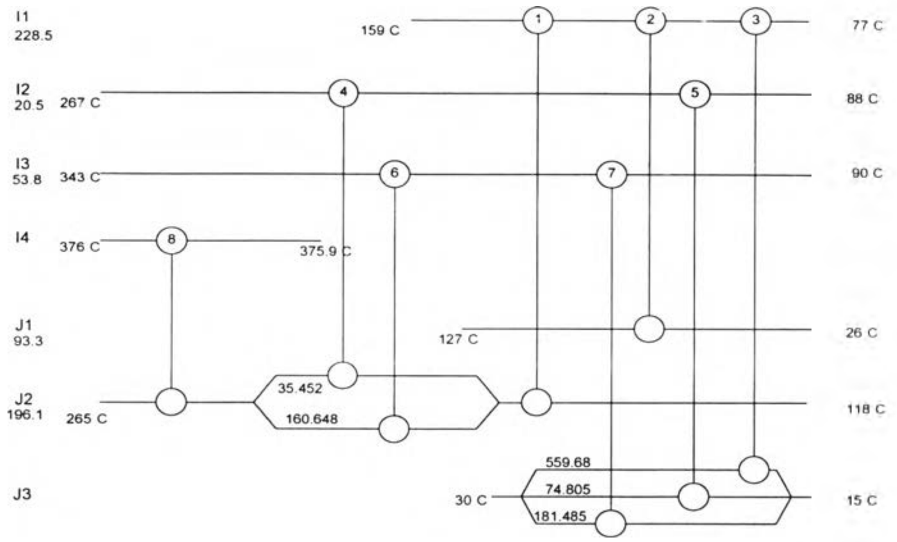


Figure 4.14 Trend of varying the number of temperature intervals for Problem 4.4 (One heat transfer zone).

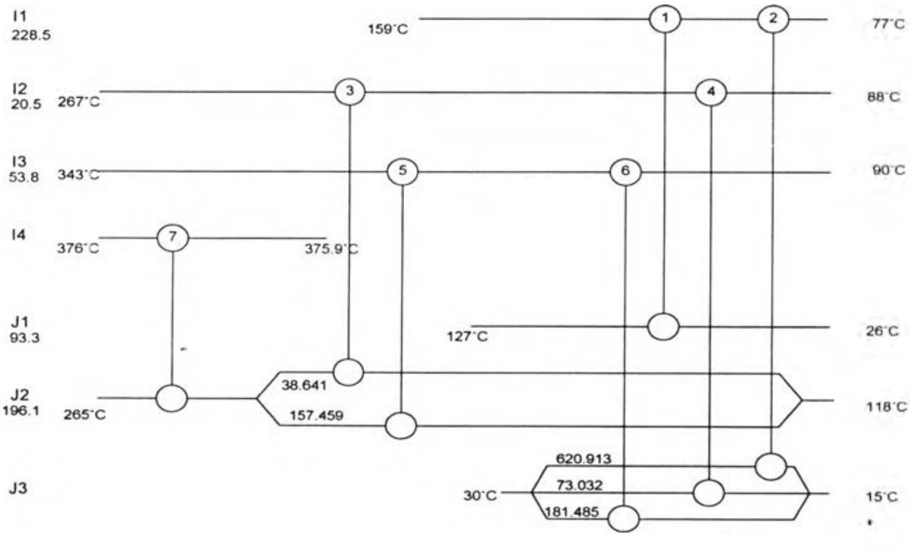
Table 4.20 Model statistics for Problem 4.4 (One heat transfer zones)

No. of Interval	67	134	165	207	236
Single Variables	1449	3870	6117	9589	10916
Discrete Variables	203	398	490	613	702
Single Equations	3684	7628	9495	12003	13844
Non Zero Elements	12539	31265	46169	68395	78190
Time to reach global optimal solution (sec)	5.656	200.078	341.671	1678.687	1394.75
Optimality Gap	0.00%	0.00%	0.00%	0.00%	0.00%



No. of heat exchanger	1	2	3	4	5	6	7	8
Heat Load (MJ/hr)	918.5	9423.3	8395.2	2529.526	1122.074	10889.12	2722.28	14489.6
Area (Prog.), (m^2)	140.441	1663.46	489.469	300.368	62.118	1052.146	170.256	300.21
Area (Actual.), (m^2)	112.8922	1653.37	483.642	327.5826	61.28325	1039.125	168.288	300.547

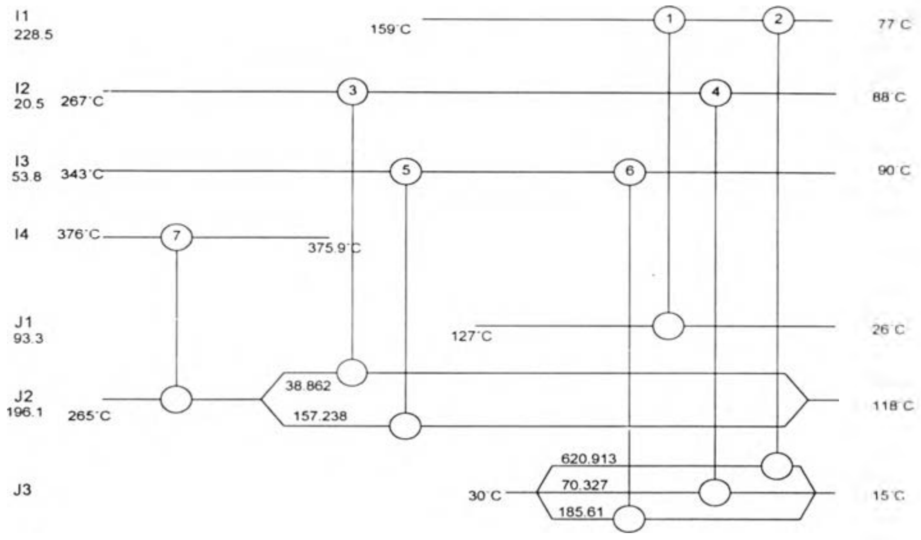
(a) 67 intervals



No. of heat exchanger	1	2	3	4	5	6	7
Heat Load (MJ/hr)	9423.3	9313.7	2556.12	1095.48	10889.12	2722.28	15381.5
Area (Prog.), (m^2)	1528.098	524.432	290.881	61.305	956.343	168.807	314.454
Area (Actual.), (m^2)	1523.968	523.461	288.454	60.20289	946.6247	168.288	314.873

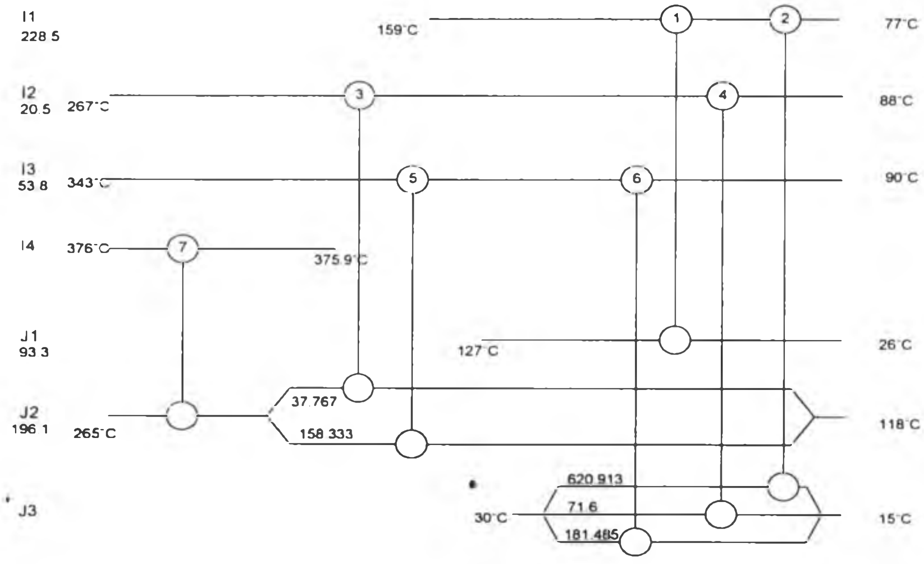
(b) 134 intervals

Figure 4.15 Heat exchanger network for Problem 4.4 with one zone of heat transfer at different number of intervals.



No. of heat exchanger	1	2	3	4	5	6	7
Heat Load (MJ/hr)	9423.3	9313.7	2596.69	1054.907	10827.25	2784.15	15402.8
Area (Prog.), (m^2)	1525.157	523.491	307.324	58.552	931.242	171.245	314.821
Area (Actual.), (m^2)	1523.968	523.461	304.862	58.53298	923.8831	171.1669	315.209

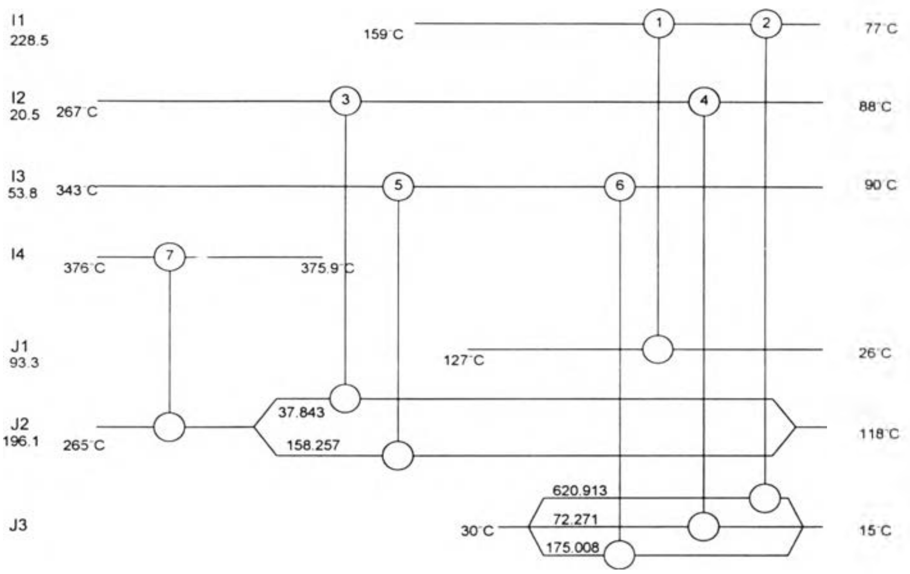
(c) 165 intervals



No. of heat exchanger	1	2	3	4	5	6	7
Heat Load (MJ/hr)	9423.3	9313.7	2577.6	1074	10889.12	2722.28	15360
Area (Prog.), (m^2)	1524.271	523.413	302.174	59.328	949.786	168.338	314.194
Area (Actual.), (m^2)	1523.968	523.461	300.782	59.3214	945.0838	168.288	314.523

(d) 207 intervals

Figure 4.15 (Cont.) Heat exchanger network for Problem 4.4 with one zone of heat transfer at different number of intervals.



No. of heat exchanger	1	2	3	4	5	6	7
Heat Load (MJ/hr)	9423.3	9313.7	2567.53	1084.069	10986.27	2625.127	15272.9
Area (Prog.), (m^2)	1523.967	523.545	296.813	59.748	988.535	163.721	312.804
Area (Actual.), (m^2)	1523.968	523.461	162.364	59.73624	984.0872	163.7119	313.146

(e) 236 intervals

Figure 4.15 (Cont.) Heat exchanger network for Problem 4.4 with one zone of heat transfer at different number of intervals.

In summary, the MILP model has an effective performance in term of the objective function stability and also generates the possible heat exchanger network design for heat exchanging process composed of various number of hot and cold process streams. According to network structure of all problems above, the total costs are eventually getting into steady even the number of temperature interval is increased. Moreover, heat exchanger network structures at any intervals of each problem are getting to be the same whereas the interval number is increased.

4.2 Retrofit for Heat Exchanger Networks

From the automatic model of new heat exchanger network design, an automatic retrofit model can be established. However, this model is also simply applied to any complex networks. We illustrate the MILP optimization using the examples of complex hot and cold process streams such as crude fractionation unit and finally compare this technique to another retrofit approach.

Testing the retrofit model that has been modified is described by using the problem 4S1. Consider a new heat exchanger network design at the temperature interval of 112 shown in Figure 4.12, we can set this network as the best optimum solution which consumes the lowest hot utility of 1,181.25 MJ/hr and cold utility of 1,101.25 MJ/hr. Then, we modified this structure to be non-optimum network which consumes higher amount of utility and use this network as the existing plant for testing retrofit algorithm. This original network for testing the retrofit model is shown in Figure 4.13. The exchanger number 2 was taken off, so heat load of this exchanger unit moved to cold utility about 2,620 MJ/hr. This modification also increases heat load of hot utility to 2,700 MJ/hr. All exchanger unit areas are kept constant as the new design structure. This modified network is used as the original one to test the retrofit model. If the retrofit model has a good performance, it would bring the network close to the best optimum design. After testing the retrofit programming model with the modified network shown in Figure 4.13, the result shows that the amount of utility consumption reduces and it also has a new unit installed at the same position as the network structure of new design, as shown in Figure 4.14. The retrofit structure is very close to the structure of the new design, 1,187.346 MJ/hr of hot utility and 1,107.346 MJ/hr of cold utility, it can concluded that the retrofit model has a good ability to find the optimum network because it can bring back the network to the new design structure similarly.

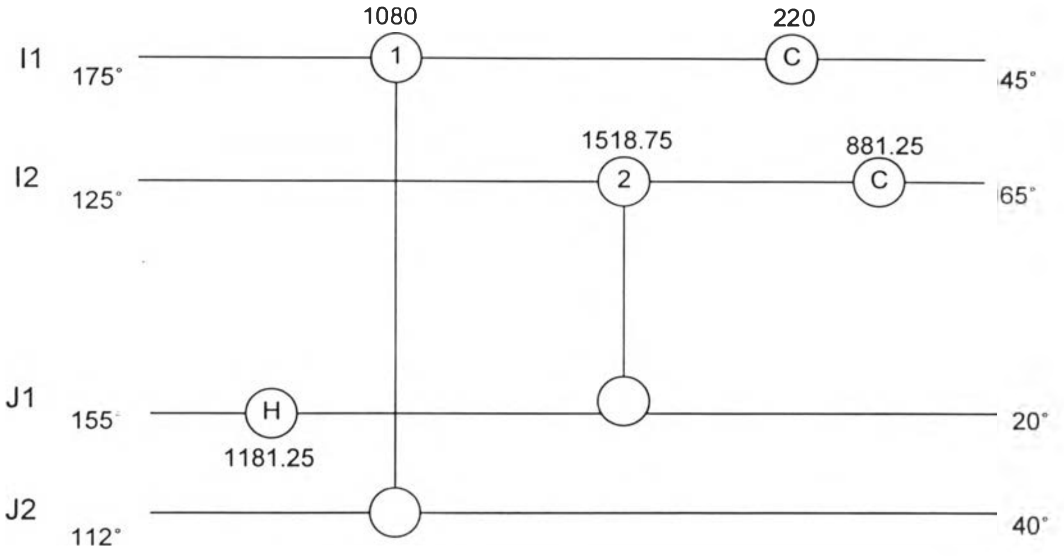


Figure 4.16 HEN design for Problem 4.1 at 112 intervals (The best optimum design).

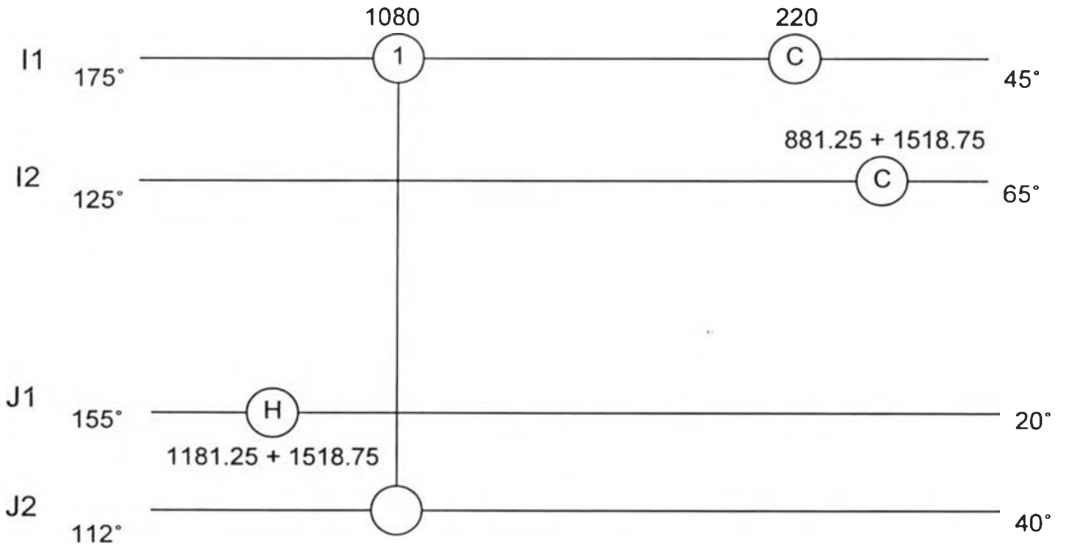


Figure 4.17 Original HEN for testing the retrofit model.

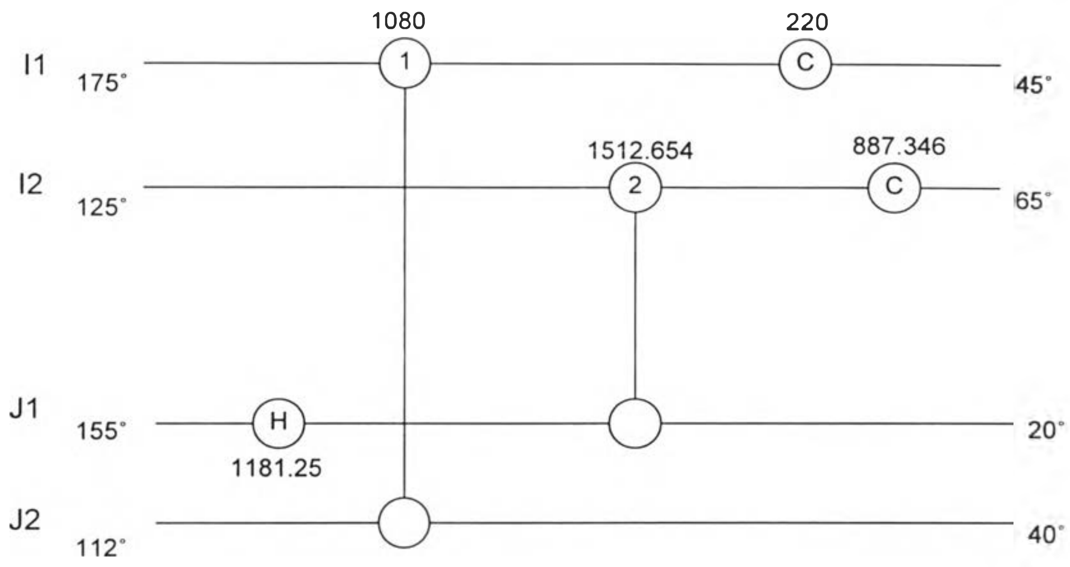


Figure 4.18 Retrofit result of HEN after testing the retrofit model.

Next, we illustrate the application examples of retrofit to demonstrate the effectiveness of the MILP approach in terms of the total cost saving.

4.2.1 Problem 4.5

This problem is taken from Ciric and Floudas (1989). It consisted of three hot and two cold process streams with one hot and one cold utilities. The stream data properties and cost data are given in Table 4.21 and Table 4.22. The existing heat exchanger network configuration, Figure 4.19, consumes 17,597 kW of hot utility and 15,510 kW of cold utility. For the retrofit solution shown in Figure 4.20, two new exchanger units are installed, 1,797.889 m^2 of area is added and 12,711.982 kW of hot utility and 10,461.982 kW of cold utility are required. The model can generate the retrofit network with 12.44% total cost saving or 246.7 k$/yr.

Table 4.21 Properties of stream for Problem 4.5

Stream	F kg./s	Cp kJ/kg-K	Tin K	Tout K	h kW/m^2-K
I1	228.5	1	432	350	0.4
I2	20.4	1	540	361	0.3
I3	53.8	1	616	363	0.25
I4		1	773	772	0.53
J1	93.3	1	299	400	0.15
J2	196.1	1	391	538	0.5
J3		1	293	313	0.53

Table 4.22 Cost data for Problem 4.5

Utilities	Cost \$/(kW-yr)
I4	95.04
J3	20
Heat Exchanger Cost	3460+171.4A \$/yr

Table 4.23 Model Statistics for Problem 4.5

Model Statistics	
Single Variables	7520
Discrete Variables	509
Single Equations	7163
Non Zero Elements	45194
Time to reach global optimal solution (sec)	1581.984
Optimality Gap	0.00%

Table 4.24 Resulting of retrofit heat exchanger for Problem 4.5

HE	Retrofit Load kW	Original Area m^2	Retrofit Area m^2	Area Addition m^2	Shell Addition	Cost $
1	9,727.041	603.710	905.565	301.855		51,737.95
2	3,884.359	584.150	865.365	281.215		48,200.25
3	5,175.983	1,001.340	1,001.340			
4	2,206.687	121.530	287.722	166.192	YES	31,945.31
5	9,380.026	1,048.280	656.063			
6	1,081.956	133.560	70.404			
7	12,711.982	246.810	186.038			
8	4,180.991		909.493	NEW		159,347.10
9	362.958		139.134	NEW		27,307.57
		3,739.38	5,021.12	34.28%	1	318,538.17

Table 4.25 Annual cost comparison between original and retrofit network for Problem 4.5

Cost ($/yr)	Existing	Retrofit
Total utility cost	1,982,618.88	1,417,386.41
Total fixed and area cost		318,538.17
Totat cost	1,982,618.88	1,735,924.58
Cost saving (%)		246,694.30 12.44%

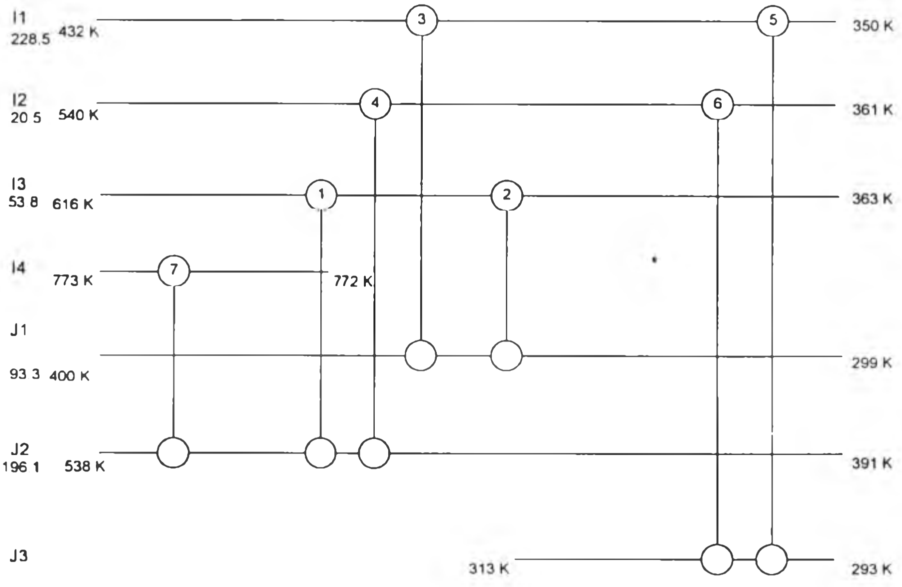


Figure 4.19 Original HEN for Problem 4.5.

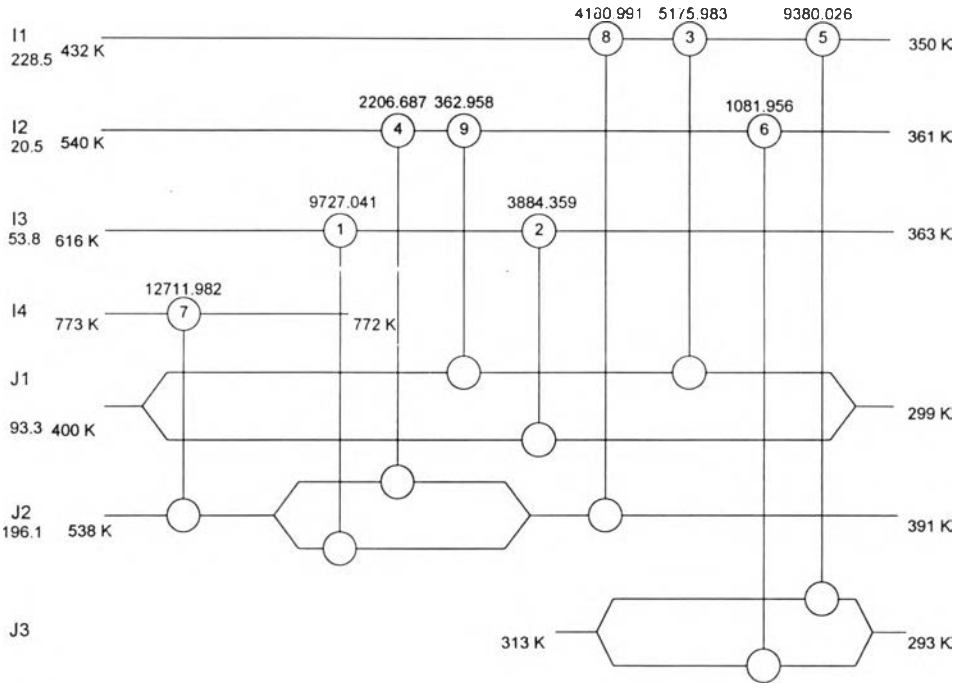


Figure 4.20 Retrofit HEN for Problem 4.5.

4.2.2 Problem 4.6

Problem 4.6 is the retrofit problem of crude distillation unit composed of 18 streams and 18 existing exchangers. Streams properties are shown in Table 4.26 and Table 4.27 while the results of retrofit network are given in Table 4.28 and 4.29. Cost comparisons are given in Table 4.30. The retrofit solution achieves 24.06% annual cost savings or 1.65 M$/yr with two new exchanger units and three shells addition. The original and retrofit networks are shown in Figure 4.21 and Figure 4.22.

Table 4.26 Stream properties for Problem 4.6

Stream	F Ton/hr	Cp KJ/kg-C	Tin C	Tout C	h MJ/h-m^2-C
I1	155.1	3.161	319.4	244.1	4.653
I2	5.695	4.325	73.24	30	18.211
I4	151.2	2.93	263.5	180.2	4.894
I7	91.81	2.262	73.24	40	4.605
I3	251.2	3.111	347.3	202.7	3.21
		2.573	202.7	45	2.278
I5	26.03	3.041	45	203.2	4.674
		2.689	203.2	110	3.952
I6	86.14	2.831	110	147.3	4.835
		2.442	147.3	50	3.8
I8	63.99	2.854	50	176	5.023
		2.606	176	120	4.846
I9	239.1	2.595	167.1	116.1	4.995
		2.372	116.1	69.55	4.88
I10	133.8	6.074	146.7	126.7	1.807
		4.745	126.7	99.94	3.373
		9.464	99.94	73.24	6.878
J1	519	2.314	30	108.1	1.858
		2.645	108.1	211.3	2.356
		3.34	211.3	232.2	2.212
J2	496.4	3.54	232.2	343.3	2.835
J3	96.87	13.076	226.2	228.7	11.971
		15.808	228.7	231.8	11.075
I11			250	249	21.6
I12			1000	500	0.4
J4			20	25	13.5
J5			124	125	21.6
J6			174	175	21.6

Table 4.27 Cost data for Problem 4.6

Utilities	Cost \$/(MJ/hr-yr)
I11	19.75
I12	37.222
J4	1.861
J5	-6.494
J6	-12.747
Heat Exchanger Cost	5291.9+77.788A \$/yr

Table 4.28 Model Statistics for Problem 4.6

Model Statistics	
Single Variables	3024
Discrete Variables	459
Single Equations	5930
Non Zero Elements	29046
Time to reach global optimal solution (sec)	6186.296
Optimality Gap	0.00%

Table 4.29 Resulting of retrofit heat exchanger for Problem 4.6

HE	Original Load MJ/hr	Retrofit Load MJ/hr	Original Area m^2	Retrofit Area m^2	Area Addition m^2	Shell Addition	Cost $
1	160,311.20	155,868.90	4,303.20	3,926.25			
2	6,903.09	6,903.09	59.40	63.80	4.40		342.03
3	17,118.40	9,628.07	33.40	21.53			
4	658.00	6,560.99	2.30	16.63	14.33	YES	6,406.84
5	2,554.70	0.02	26.30	28.93	2.63		204.58
6	2,410.70	9,902.58	24.60	398.53	373.93	YES	34,379.01
7	1,065.04	1,065.04	5.50	5.87	0.37		28.70
8	45,024.40	6,042.97	145.00	41.66			
9	100,642.70	63,561.25	1,212.70	962.01			
10	4,473.60	4,045.64	93.70	93.70			
11	54,618.70	59,060.59	685.70	1,239.90	554.20	YES	48,402.09
12	6,293.80	3,373.45	40.00	44.00	4.00		311.15
13	58,044.30	58,042.28	183.30	182.39			
14	36,903.20	36,903.23	101.60	101.47			
15	36,917.40	0	93.90	0			
16	67,053.08	67,053.08	278.10	288.97	10.87		845.32
17	7,913.77	7,913.77	53.50	52.24			
18	136,138.80	95,207.49	976.40	709.00			
19		36,917.41		727.96			61,918.53
20		38,981.58		651.93			56,004.54
			8,318.60	9,556.76	14.88%	3	208,842.80

Table 4.30 Annual cost comparison between original and retrofit network for Problem 4.6

Cost $/yr	Existing	Retrofit
Total utility cost	6,865,616.51	5,004,800.23
Total fixed and area cost	-	208,842.80
Totat cost	6,865,616.51	5,213,643.03
Cost saving	1,651,973.479	24.06%

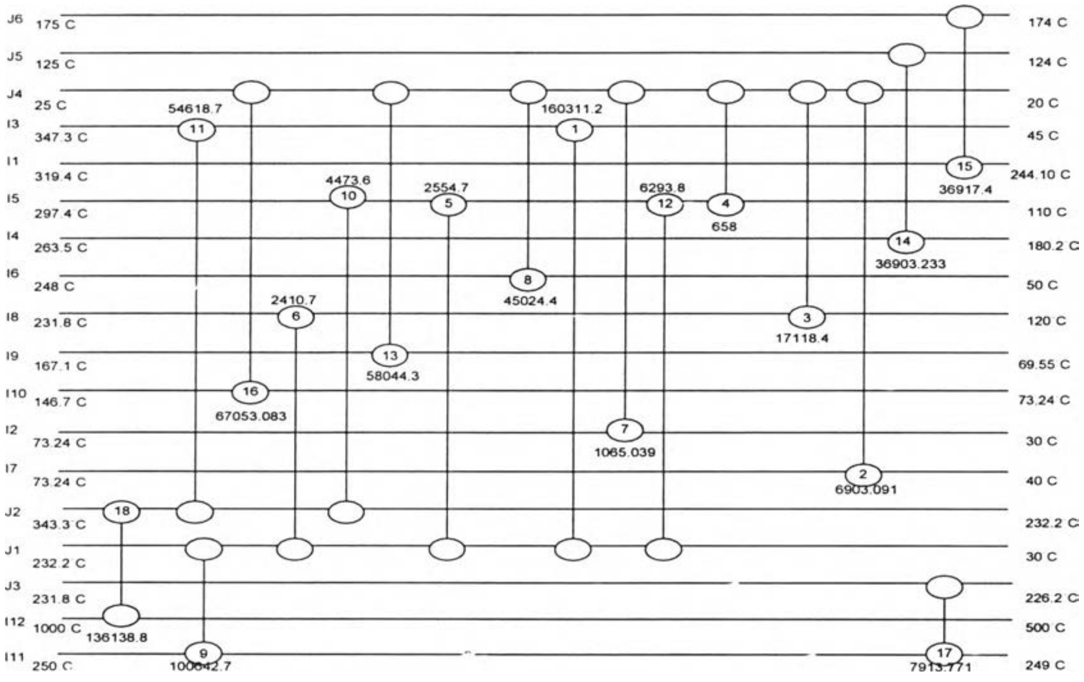


Figure 4.21 Original HEN for Problem 4.6.

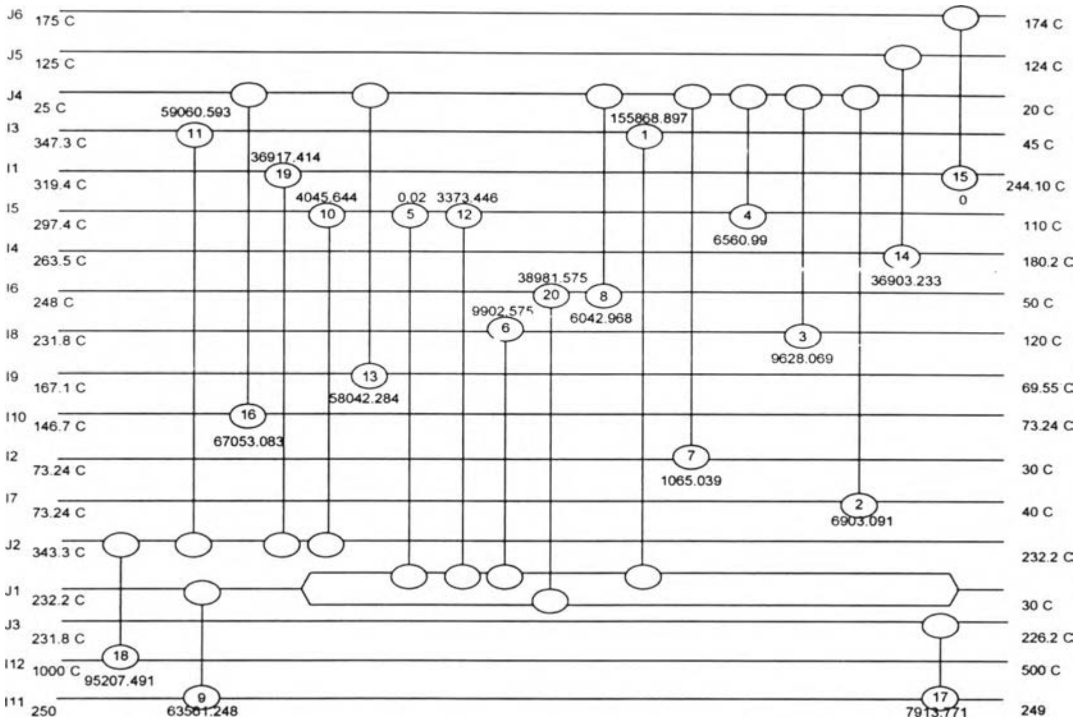


Figure 4.22 Retrofit result of HEN for Problem 4.6.

4.2.3 Problem 4.7

We now compare our method with Hypertargets (Briones and Kokossis, 1999). Table 4.31 shows the stream and cost data for crude distillation unit consisting of 12 streams and 11 existing units. Figure 4.23 shows the original network and Figure 4.24 shows the retrofit structure generated by our MILP strategy. Hypertargets established two retrofit designs (B1 and B2) with the same utility cost and one new unit in each case. They are shown in Figure 4.25 and 4.26. Our MILP approach suggests using two new smaller exchangers and more utility. The results are shown in Tables 4.32 and 4.33 and the total annual cost in Table 4.34. The retrofit has a 4.17% saving over the original structure. The results show that the retrofit network generated by an MILP model also gives lower cost than Hypertargets approach.

Table 4.31 Stream and cost data for Problem 4.7

Stream	FCp kW/C	Tin C	Tout C	h kW/m^2-C
I1	470.00	140.00	40.00	0.8
I2	825.00	160.00	120.00	0.8
I3	42.42	210.00	45.00	0.8
I4	100.00	260.00	60.00	0.8
I5	357.14	280.00	210.00	0.8
I6	50.00	350.00	170.00	0.8
I7	136.36	380.00	160.00	0.8
J1	826.09	270.00	385.00	0.8
J2	500.00	130.00	270.00	0.8
J3	363.64	20.00	130.00	0.8
I8		500.00	499.00	0.8
J4		20.00	40.00	0.8

Note: Exchanger cost=300xArea; stream cost=60$/kW yr, cooling water cost=5$/kW yr

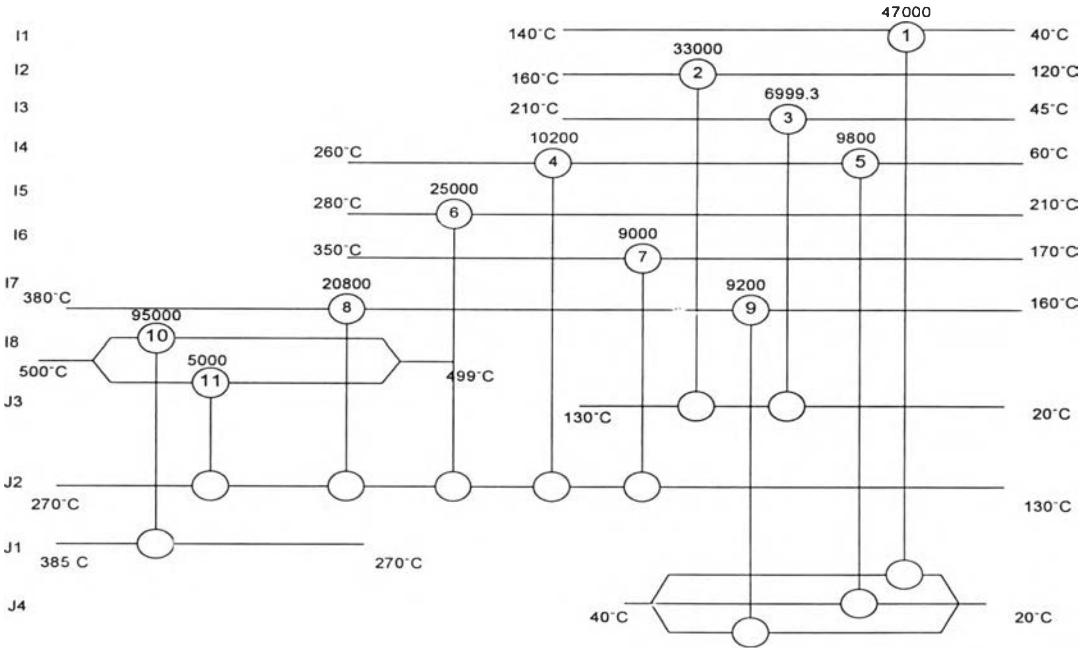


Figure 4.23 Original HEN for Problem 4.7.

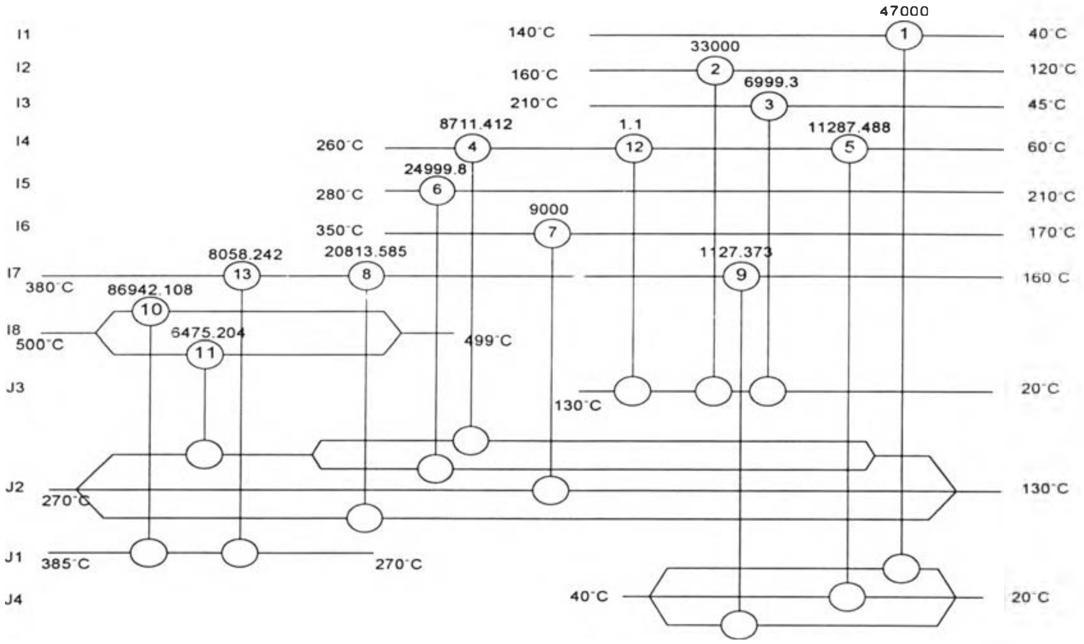


Figure 4.24 Retrofit HEN for Problem 4.7.

Table 4.32 Model statistics for Problem 4.7

Model Statistics	
Single Variables	3120
Discrete Variables	382
Single Equations	6347
Non Zero Elements	23949
Time to reach global optimal solution (sec)	428.625
Optimality Gap	0.00%

Table 4.33 Resulting of retrofit heat exchanger network for Problem 4.7

HE	Original Load MJ/hr	Retrofit Load MJ/hr	Original Area m^2	Retrofit Area m^2	Area addition m^2	Shell Addition	Cost $
1	47000	47000	2363.862	2402.060	38.198		
2	33000	33000	1609.621	1613.931	4.310	YES	1,293.106
3	7000	7000	230.691	242.319	11.628	YES	3,488.465
4	10200	8711.412	692.139	692.139			
5	9800	11287.488	339.798	366.255	26.457		
6	25000	25000	1226.755	1286.336	59.581	YES	17,874.203
7	9000	9000	224.915	396.584	171.669	YES	51,500.690
8	20800	20813.585	1211.000	1211.000			
9	9200	1127.373	141.471	20.484			
10	95000	86942.108	1434.979	1344.353			
11	5000	6475.204	53.311	66.928	13.617		4,084.965
12		1.1		0.051	NEW		15.300
13		8058.242		298.330	NEW		89,499.000
			9528.542971	9940.77	4.33%	4	167,755.729

Table 4.34 Annual cost comparison between Hypertargets and MILP algorithm

Cost $/yr	Existing	Hypertarget B1	Hypertarget B2	MILP
Total utility cost	6,330,000	5,607,200	5,607,200	5,902,113
Total fixed and area cost		531,900	576,720	163,671
Totat cost	6,330,000	6,139,100	6,183,920	6,065,784
MILP more saving ($/yr)	264,216 4.17%	73,316 1.19%	118,136 1.91%	

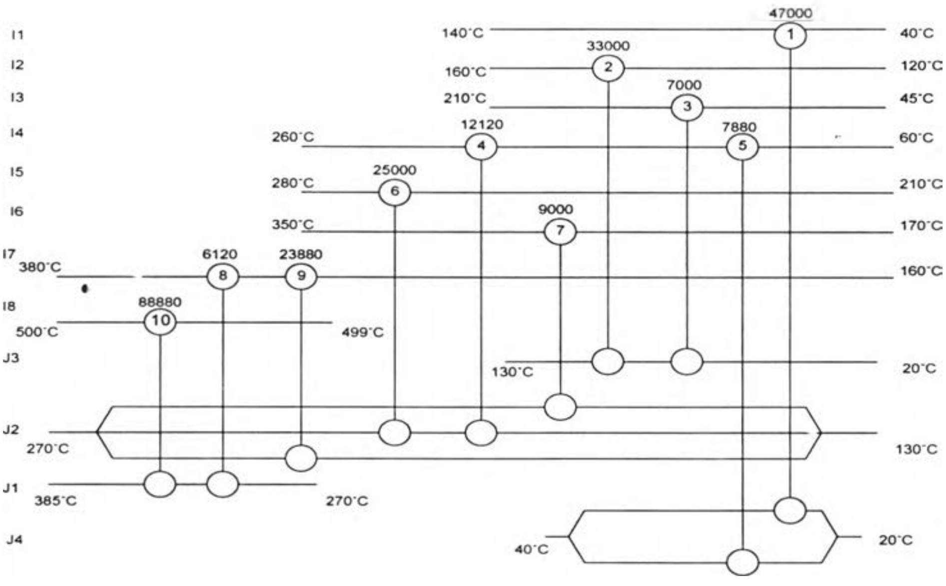


Figure 4.25 Hypertargets retrofit designs B1.

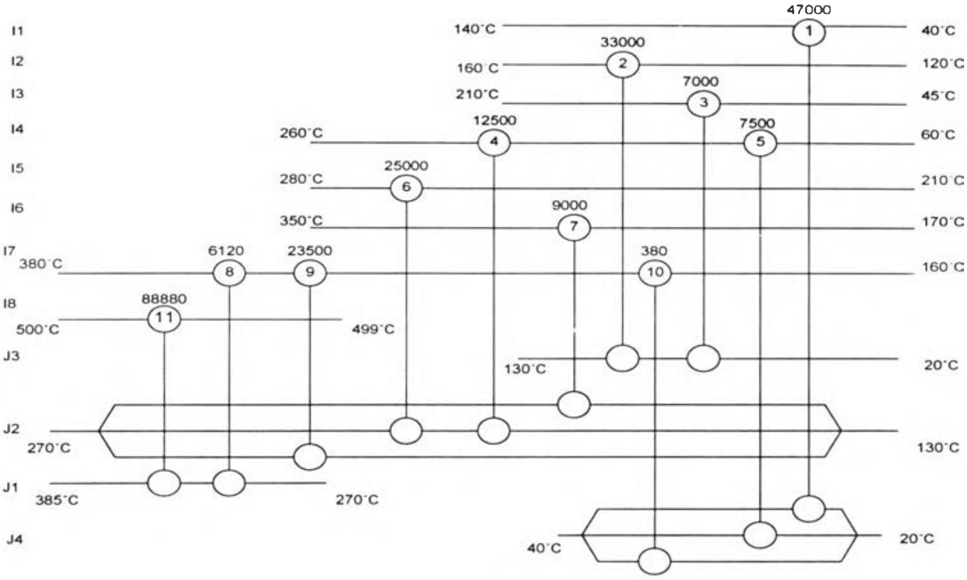


Figure 4.26 Hypertargets retrofit designs B2.

4.3 Additional Topics for HEN Retrofits

4.3.1 Parallel/Series Position for The New Exchanger Installation

The benefit position of a new exchanger installation is considered here. We use the problem 4.6 to illustrate this situation. A new exchanger unit can be installed parallel or series with other units. Following the retrofit results of the problem 4.6, there are two new exchanger units presented. First unit, exchanger number 19, is settled on the cold stream J2 and the latter, no. 20, is installed on the cold stream J1. So, we simulate the model with the constraint of allowed splitting both cold stream J1 and J2 to consider the effect of using the new exchanger in parallel. In contrast, non-splitting both cold streams J1 and J2 are applied when settling the new exchanger in series. The results for series and parallel position are shown in Figure 4.27 and 4.28. Table 4.39 shows that parallel installation of new exchanger unit gives more benefit than settling the unit in series. Because it has higher temperature difference between hot and cold streams, so heat transfer for the parallel exchanger is greater. Therefore, the network of parallel installation of new exchanger consumes lower amount of utility, but fixed and area costs are higher. However, the overall cost for retrofit network equipped with parallel new exchanger is less than the network set up the new units in series.

Table 4.35 Model statistics for Problem 4.6 with non-splitting cold stream

Model Statistics	
Single Variables	2902
Discrete Variables	459
Single Equations	5019
Non Zero Elements	25677
Time to reach global optimal solution (sec)	766.906
Optimality Gap	0.00%

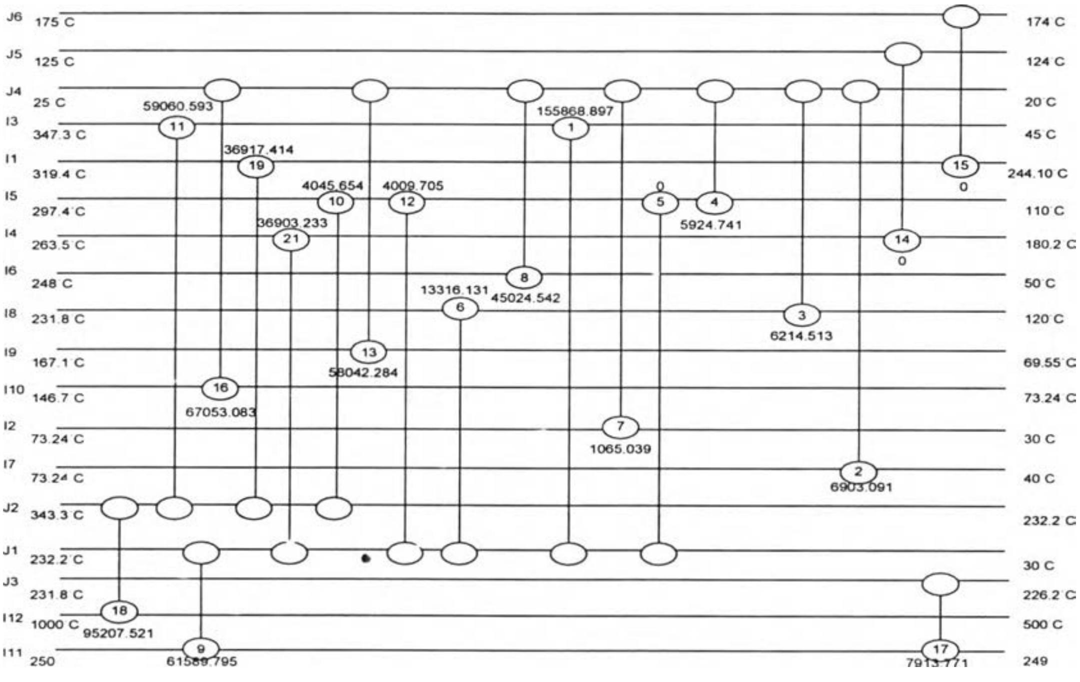


Figure 4.27 Retrofit HEN for Problem 4.6 with non-splitting cold stream.

Table 4.36 Model statistics for Problem 4.6 with splitting cold stream

Model Statistics	
Single Variables	3043
Discrete Variables	459
Single Equations	6049
Non Zero Elements	29457
Time to reach global optimal solution (sec)	27165.45
Optimality Gap	0.00%

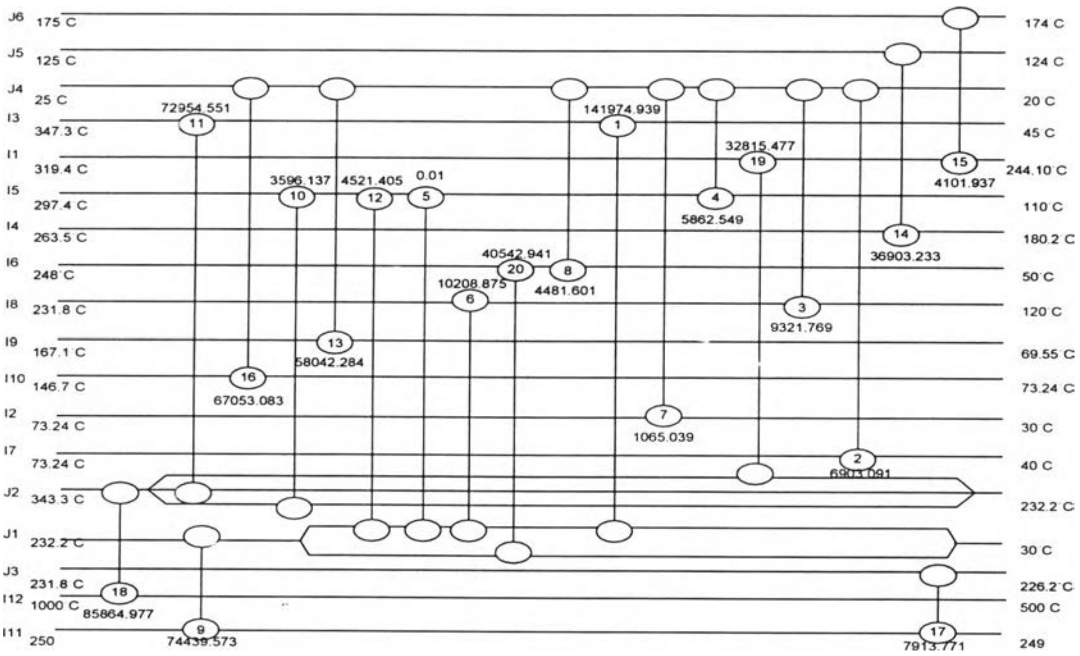


Figure 4.28 Retrofit HEN for Problem 4.6 with splitting cold stream.

Table 4.37 Resulting of retrofit HEN for non-splitting cold stream

HE	Original Load MJ/hr	Retrofit Load MJ/hr	Original Area m^2	Retrofit Area m^2	Area Addition m^2	Shell Addition	Cost $
1	160,311.20	155,868.90	4,303.20	3,914.57			
2	6,903.09	6,903.09	59.40	63.80	4.40		342.03
3	17,118.40	6,214.51	33.40	15.12			
4	658.00	5,924.74	2.30	15.48	13.18	YES	6,316.91
5	2,554.70	0.00	26.30	0.00			
6	2,410.70	13,316.13	24.60	300.48	275.88	YES	26,751.98
7	1,065.04	1,065.04	5.50	5.87	0.37		28.70
8	45,024.40	45,024.54	145.00	146.59	1.59		123.45
9	100,642.70	61,589.80	1,212.70	946.88			
10	4,473.60	4,045.65	93.70	93.70			
11	54,618.70	59,060.59	685.70	1,239.90	554.20	YES	48,402.09
12	6,293.80	4,009.71	40.00	44.00	4.00		311.15
13	58,044.30	58,042.28	183.30	182.39			
14	36,903.20	0	101.60	0			
15	36,917.40	0	93.90	0			
16	67,053.08	67,053.08	278.10	288.97	10.87		845.32
17	7,913.77	7,913.77	53.50	52.24			
18	136,138.80	95,207.52	976.40	709.00			
19		36,917.41		727.96			61,918.45
20							
21		36,903.23		683.36			58,448.95
			8,318.60	9,430.29	13.36%	3	203,489.04

Table 4.38 Resulting of retrofit HEN for splitting cold stream

HE	Original Load MJ/hr	Retrofit Load MJ/hr	Original Area m^2	Retrofit Area m^2	Area Addition m^2	Shell Addition	Cost $
1	160,311.200	141,974.939	4,303.20	3,673.432			
2	6,903.091	6,903.091	59.40	63.797	4.397		342.03
3	17,118.400	9,321.769	33.40	21.017			
4	658.000	5,862.549	2.30	15.353	13.053	YES	6,307.27
5	2,554.700	0.010	26.30	28.930	2.63		204.58
6	2,410.700	10,208.875	24.60	312.588	287.988	YES	27,693.91
7	1,065.039	1,065.039	5.50	5.369	0.369		28.70
8	45,024.400	4,481.601	145.00	30.893			
9	100,642.700	74,439.573	1,212.70	1,045.482			
10	4,473.600	3,596.137	93.70	188.880	95.18	YES	12,695.76
11	54,618.700	72,954.551	685.70	2,220.875	1,535.18	YES	124,710.09
12	6,293.800	4,521.405	40.00	44.000	4		311.15
13	58,044.300	58,042.284	183.30	182.391			
14	36,903.200	36,903.233	101.60	101.472			
15	36,917.400	4,101.937	93.90	13.138			
16	67,053.083	67,053.083	278.10	288.967	10.867		845.32
17	7,913.771	7,913.771	53.50	52.239			
18	136,138.800	85,864.977	976.40	643.700			
19		32,815.477		845.518	NEW		71,063.05
20		40,542.941		724.634	NEW		61,659.73
			8,318.60	10,503.18	26.10%	4	305,861.61

Table 4.39 Cost comparison between parallel and series placement of the new exchanger

Cost $/yr	Existing	Retrofit non-splitting	Retrofit splitting
Total utility cost	6,865,616.51	5,270,522.77	4,814,837.18
Total fixed and area cost	-	203,489.04	305,861.61
Totat cost	6,865,616.51	5,474,011.81	5,120,698.79
Cost saving		20.27%	25.42%

4.3.2 Allowed and Forbidden Matches of Hot and Cold Streams

If pairs of hot and cold streams are not allowed to exchange heat for the reasons such as safety, operability, piping difficulties, contamination prevention, etc. Using mathematical programming, it is extremely simple to formulate the allowed and forbidden matching situations. We presented the problem 4.5 to illustrate the forbidden match of hot and cold stream. Figure 4.20 shows the original retrofit structure that allowed matching of hot stream I1 and cold stream J2. In this situation, we presume forbidden match between hot stream I1 and cold stream J2. The new retrofit solution for heat exchanger network is shown in Table 4.40 and Table 4.41. The retrofit structure for forbidden match is shown in Figure 4.29. Time consuming for the constraint of forbidden match (I1,J2) is less than the constraint of allowed matching. The overall cost for the retrofit structure with forbidden match is higher than the total cost of retrofit with allowed matching structure.

Table 4.40 Model statistics for retrofit with forbidden match (I1,J2)

Model Statistics	
Single Variables	7387
Discrete Variables	490
Single Equations	6904
Non Zero Elements	44241
Time to reach global optimal solution (sec)	673.859
Optimality Gap	0.00%

Table 4.41 Resulting of retrofit with forbidden match (I1,J2)

HE	Retrofit Load kW	Original Area m^2	Retrofit Area m^2	Area Addition m^2	Shell Addition	Cost $
1	11,342.833	603.710	1,180.24	576.53	YES	102,276.90
2	2,268.567	584.150	348.77			
3	7,154.733	1,001.340	1,277.37	276.03		47,312.06
4	2,704.889	121.530	366.79	245.26	YES	45,498.08
5	11,582.267	1,048.280	756.16			
6	946.711	133.560	62.81			
7	14,778.978	246.810	212.40			
		3,739.38	4,204.54	12.44%	2	195,087.03

Table 4.42 Annual cost comparison between original retrofit and retrofit with forbidden match (I1,J2)

Cost ($/yr)	Existing	Retrofit	Retrofit (forbid I1,J2)
Total utility cost	1,982,618.88	1,417,386.41	1,655,173.63
Total fixed and area cost		318,538.17	195,087.03
Totat cost	1,982,618.88	1,735,924.58	1,850,260.66
Cost saving		246,694.30	132,358.22
(%)		12.44%	6.68%

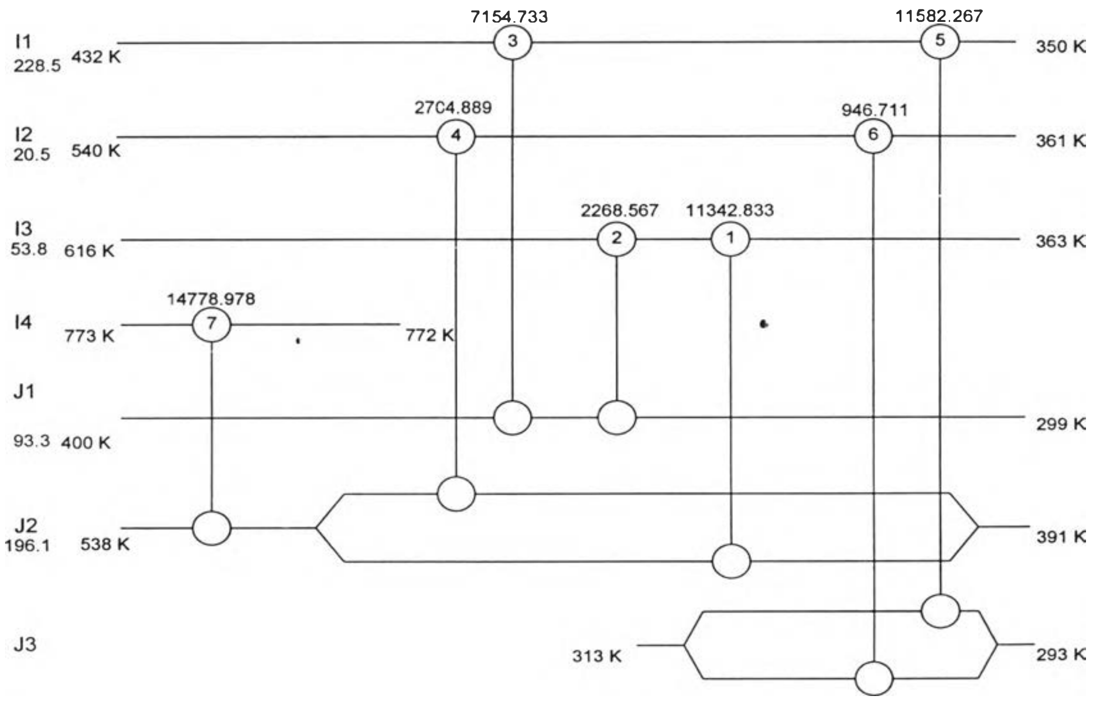


Figure 4.29 Retrofit HEN with forbidden match (I1,J2) for Problem 4.5

4.3.3 Relocation of Existing Heat Exchangers

In special occasions, the overall cost of retrofit heat exchanger network can be further reduced by rearrangement of the original exchanger from the existing match (i,j) to the new match (i',j') of hot and cold stream. We used problem 4.5 to illustrate the retrofit relocation topology.

For the retrofit relocation model, we need to specify the binary variable $\delta_{ij}^{z,k}$ which identify which exchangers are needed to relocate. In this example, we first consider the retrofit structure without relocation in Figure 4.20. In Table 4.24, consider an exchanger number 5 which has the original area larger than the area required in retrofit network and look to an exchanger number 1, it required to add the exchanger area. So, it has cost reduction possibility when we relocate the exchanger 5 to the position of exchanger unit number 1. Then, we proposed to specify the $\delta_{ij}^{z,k}$ of these two repositioning, the exchanger number 1 and number 5.

The network structure for relocation is shown in Figure 4.30. The retrofit HEN with relocation topology can generate the structure with 16.29% total cost saving whereas the retrofit without relocation can save around 12.44%. Additionally, we also compare the MILP performance with the retrofit solution from the approach of Ciric et al. (1989) and Kin-Lung Ma et al. (2000). Their retrofit solutions are given in Figure 4.31 and Figure 4.32. Table 4.47 shows that the MILP model gives the highest annual cost saving for retrofit HEN.

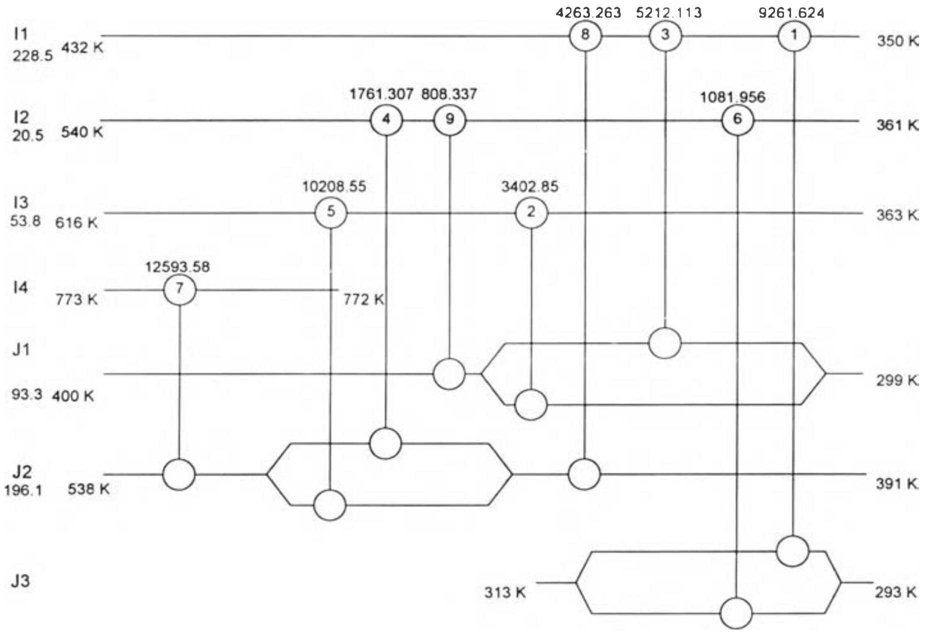


Figure 4.30 Retrofit HEN with relocation for Problem 4.5.

Table 4.43 Model statistics for Problem 4.5 with relocation

Model Statistics	
Single Variables	7524
Discrete Variables	502
Single Equations	7162
Non Zero Elements	45180
Time to reach global optimal solution (sec)	950.234
Optimality Gap	0.00%

Table 4.44 Resulting of retrofit heat exchanger with relocation for Problem 4.5

HE	Retrofit Load MJ/hr	Original Area m^2	Retrofit Area m^2	Area Addition m^2	Relocation	Shell Addition/ New Exchanger	Cost $
1	9,261.624	603.71	608.74	5.03	YES		862.14
2	3,402.850	584.15	746.32	162.168			27,795.60
3	5,212.113	1,001.34	1,001.34				
4	1,761.307	121.53	182.30	60.765			10,415.12
5	10,208.550	1,048.28	1,103.79	55.511	YES		9,514.59
6	1,081.956	133.56	70.61				
7	12,593.580	246.81	184.51				
8	4,263.263		946.22			NEW	165,642.62
9	808.337		223.08			NEW	41,695.40
		3,739.38	5,066.91	35.50%		2	255,925.46

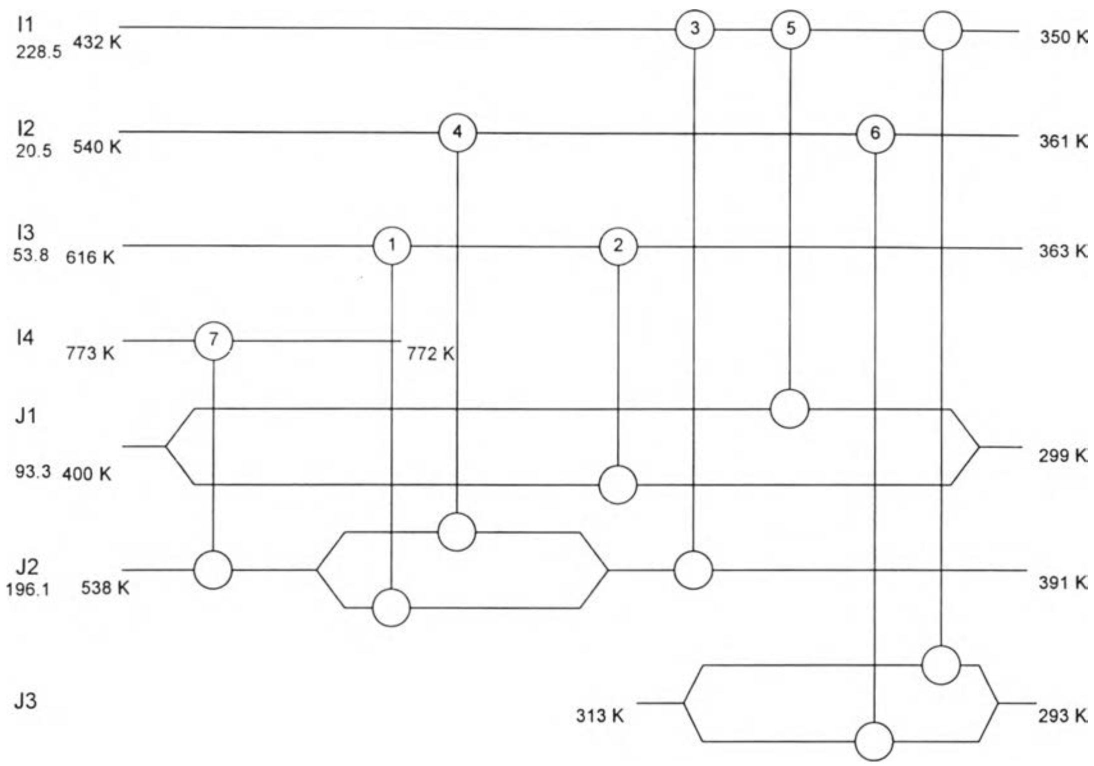


Figure 4.31 Retrofit HEN by Ciric and Floudas (1989).

Table 4.45 Resulting of Retrofit HEN by Ciric and Floudas (1989)

HE	Retrofit Load kW	Original Area m^2	Retrofit Area m^2	Area Addition m^2
1	9,899	603.71	991.32	387.61
2	3,712	584.15	927.22	343.07
3	4,314	1,001.34	946.18	
4	2,203	121.53	276.35	154.82
5	5,711	1,048.28	1,218.95	170.67
6	1,612	133.56	123.91	
7	12,410	246.81	182.11	
new	8,711		755.80	755.80
		3,739.38	5,421.84	44.99%

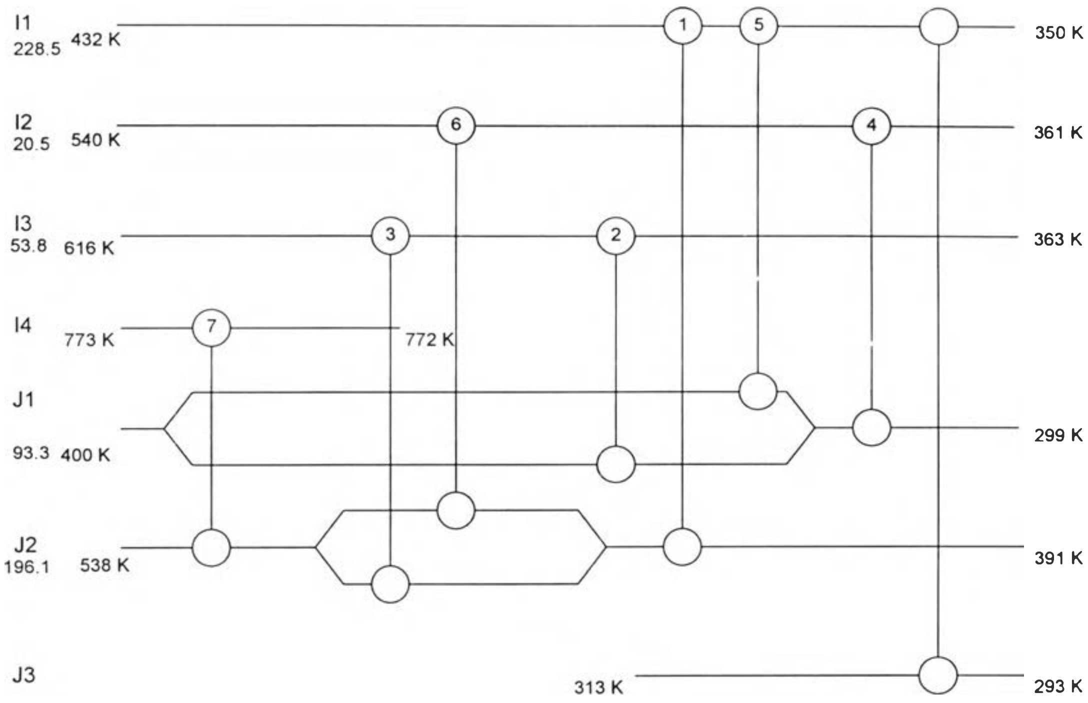


Figure 4.32 Retrofit HEN by Kin-Lung Ma et al. (2000).

Table 4.46 Resulting of Retrofit HEN by Kin-Lung Ma et al. (2000)

HE	Retrofit Load kW	Original Area m^2	Retrofit Area m^2	Area Addition m^2
1	4,070	603.71	844.51	240.8
2	3,601	584.15	1000.01	415.86
3	10,010	1001.34	1001.34	
4	1,458	121.53	185.49	63.96
5	4,364	1048.28	1048.28	
6	2,356	133.56	391.54	257.98
7	12,390	246.81	181.82	
new	10,303		657.17	657.17
		3739.38	5310.16	42.00%

Table 4.47 Cost comparison for retrofit relocation algorithm

Cost ($/yr)	Existing	Retrofit		
		MILP	Ciric et al.	Kin-Lung Ma et al.
Total utility cost	1,982,618.88	1,403,765.44	1,385,906.00	1,383,605.00
Total fixed and area cost		255,925.46	321,000.00	287,071.00
Totat cost	1,982,618.88	1,659,690.90	1,706,906.00	1,670,676.00
Cost saving		322,927.98	275,712.88	311,942.88
(%)		16.29%	13.91%	15.73%

However, there is a limitation for the relocation topology. Sometimes, we can not improve the annualized cost with exchanger repositioning. The designer should be certain that the total cost would be diminished if you change the original exchanger to the new matching position.