CHAPTER VI
RESULT AND DISCUSSION

Five examples of different sizes are presented to verify the proposed improved stage-wise superstructure model and to determine the efficiency of the proposed model. These examples were implemented in GAMS (version 24.2.1) and solved by DICOPT on a PC machine (i7 2.00GHz, 8 GB RAM, 64 bit-Operation system). The number of main-stage and sub-stage that were used for this work, are set at the solving limitation of GAMS program (4 main-stage and 5 sub-stage).

6.1 Examples from Literature

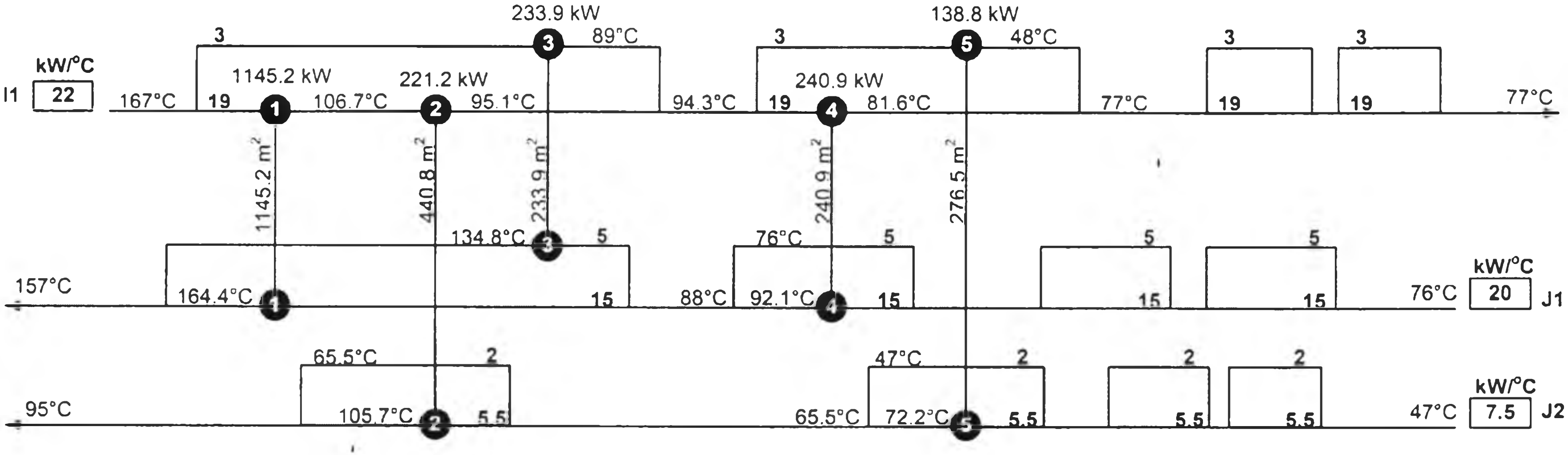
6.1.1 Example 1

This example was taken from Huang and Karimi (2012). It involves with one hot process stream (I1), two cold process streams (J1-J2), one hot utility, and one cold utility. The data for this example is presented in Table 6.1. The Heat exchanger cost ($) is 6,600+670(Area)$^{0.83}$.

Table 6.1 Example 1 data.

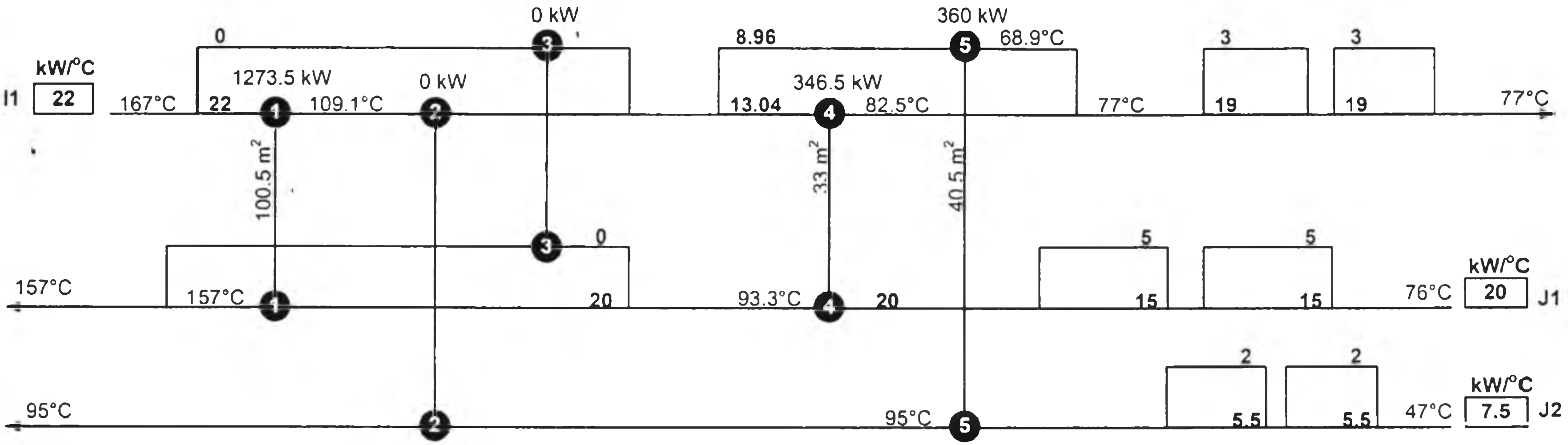
Stream	TIN(°C)	TOUT(°C)	h(kW/m^2-°C)	F(kW/°C)	Cost($/kW-yr)
I1	167	77	2	22	-
J1	76	157	2	20	-
J2	47	95	0.67	7.5	-
CU	27	47	1	-	20
HU	227	227	1	-	120

EMAT = 1°C



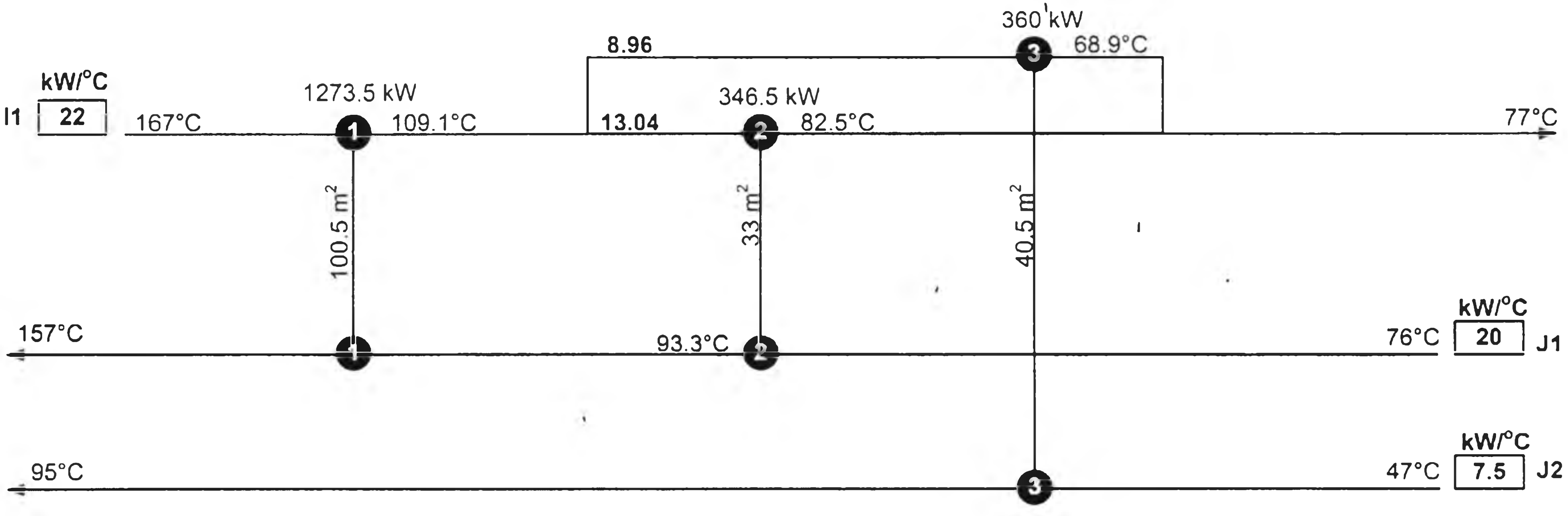
Total area (m^2)	2,337.3
Annualized utility cost	-
Investment cost	\$756,955
Total annualized cost	\$756,955

Figure 6.1 First Heat Exchanger Configuration result from First MILP, First NLP, and Second MILP of Example 1.



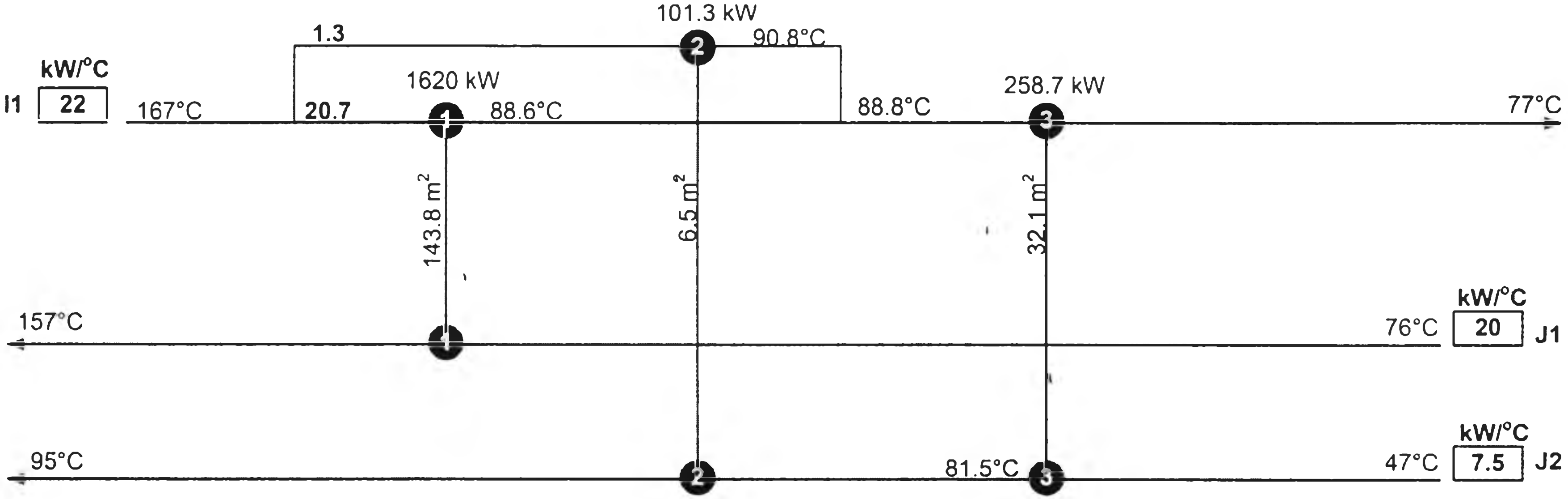
Total area (m^2)	174
Annualized utility cost	-
Investment cost	\$73,695
Total annualized cost	\$73,695

Figure 6.2 First Heat Exchanger Configuration result from Second NLP of Example 1.



Total area (m^2)	174
Annualized utility cost	-
Investment cost	$73,695
Total annualized cost	$73,695

Figure 6.3 Best Heat Exchanger Configuration result from MINLP of Example 1.



Total area (m^2)	182.5
Annualized utility cost	-
Investment cost	$76,327
Total annualized cost	$76,327

Figure 6.4 Best Heat Exchanger Configuration result from Huang and Karimi (2012) of Example 1.

Although we obtained the same number of exchangers as different from their HENs. Our TAC is \$73,684 with a total area of 174 m^2 which are lower than the results from Huang and Karimi (2012) (\$76,327, area = 182.5 m^2) It showed that with a better TAC and area at the first iteration. This example show that provinding arised due to solving MINLP with good feasible initial point can help obtianing better solution.

The HEN configuration obtained from First MILP, First NLP, and Second MILP (Figure 6.1) are the same. This case can be happened when the first initial flow variables satisfy the next NLP.

From Figure 6.2, all the by-pass streams are eliminated from all stages where no heat exchanger exists. From this step, the result from solving Second NLP, except branch flow variables, which are obtained from Second MILP, are used as initial values for solving MINLP.

By comparing our solution with the result from Huang and Karimi (2012) (Figures 6.3 and 6.4), this example illustrated that synthesizing HEN problem with good feasible initial points can result in obtaining a better solution.

Table 6.2 Comparison of example 1 result of our model with literature

Comparison	Our model	Huang and Karimi (2012)	Björk and Westerlund (2002)
Total area(m^2)	174	182.5	Not report
Number of HE	3	3	3
Annualized utility cost(\$)	-	-	-
Investment cost(\$)	73,695	76,327	76,330
TAC(\$)	73,695	76,327	76,330
Max CPU time(s)	2,978	3,600	938

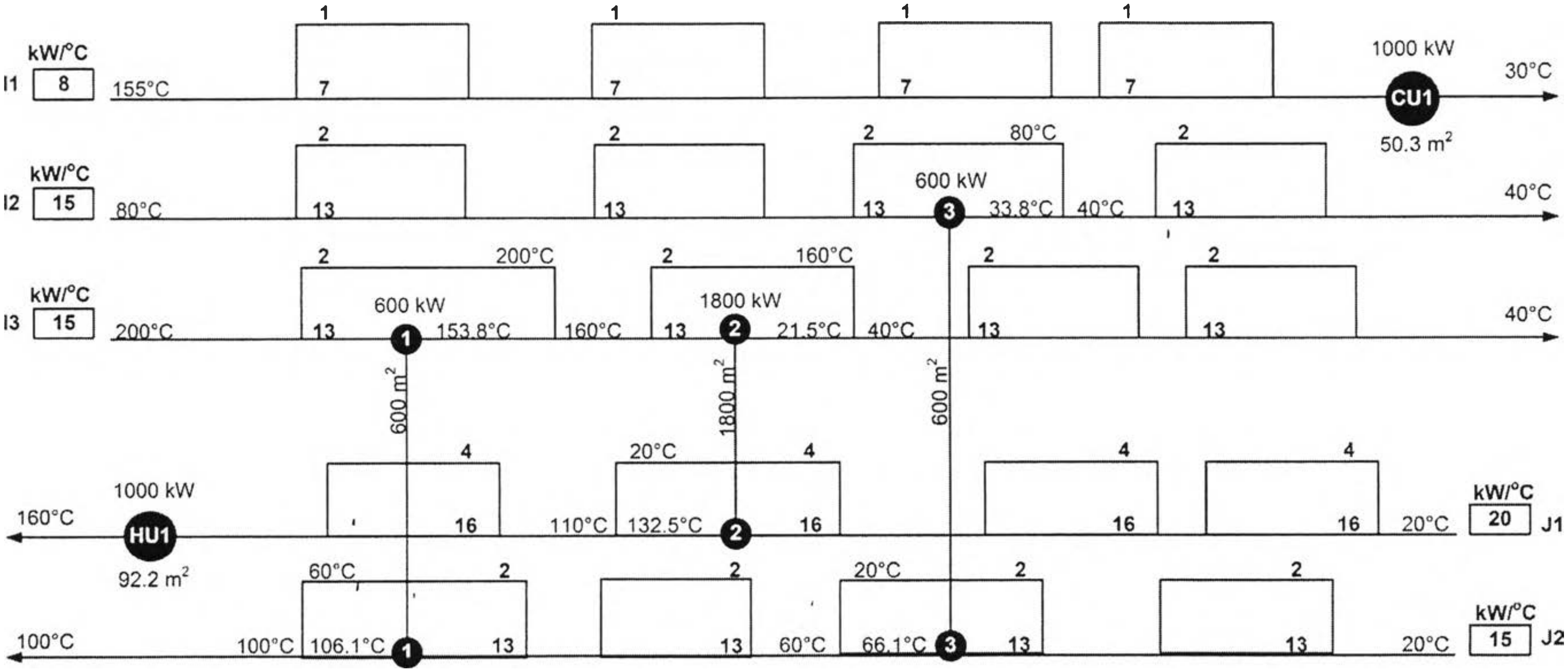
6.1.2 Example 2

This example was taken from Björk and Westerlund (2002). They used this example to illustrate the impact of non-isothermal mixing. The problem consists of three hot streams, two cold streams, one hot utility and one cold utility. The data for this example is presented in Table 6.3. The Heat exchanger cost ($) is 6,000+600(Area)$^{0.85}$. Our model yields a HEN with four exchangers and a TAC of $94,880 which is slightly lower than the best network reported in literature(Björk *et al.*, 2002; Huang *et al.*, 2012). While Björk and Westerlund (2002) reported the same HEN configuration as their best network with a TAC of $96,001. Huang and Karimi (2012) also solved the same problem and obtained the same HEN configuration as Björk and Westerlund (2002) with a TAC of $95,643 as summarized in Table 6.4.

Table 6.3 Example 2 data

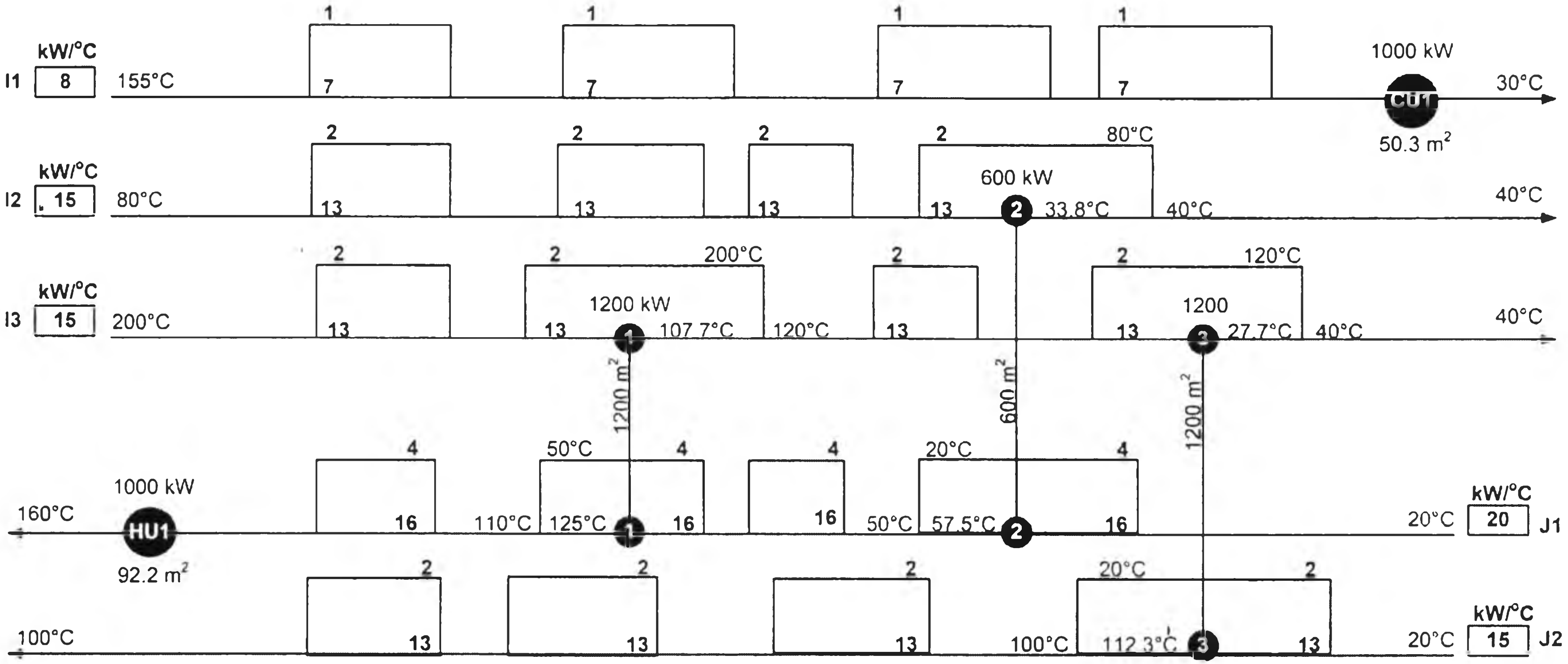
Stream	TIN(°C)	TOUT(°C)	h(kW/m^2-°C)	F(kW/°C)	Cost($/kW-yr)
I1	155	30	2	8	-
I2	80	40	2	15	-
I3	200	40	2	15	-
J1	20	160	2	20	-
J2	20	100	2	15	-
CU	290	300	2	-	20
HU	680	680	2	-	120

EMAT = 1°C



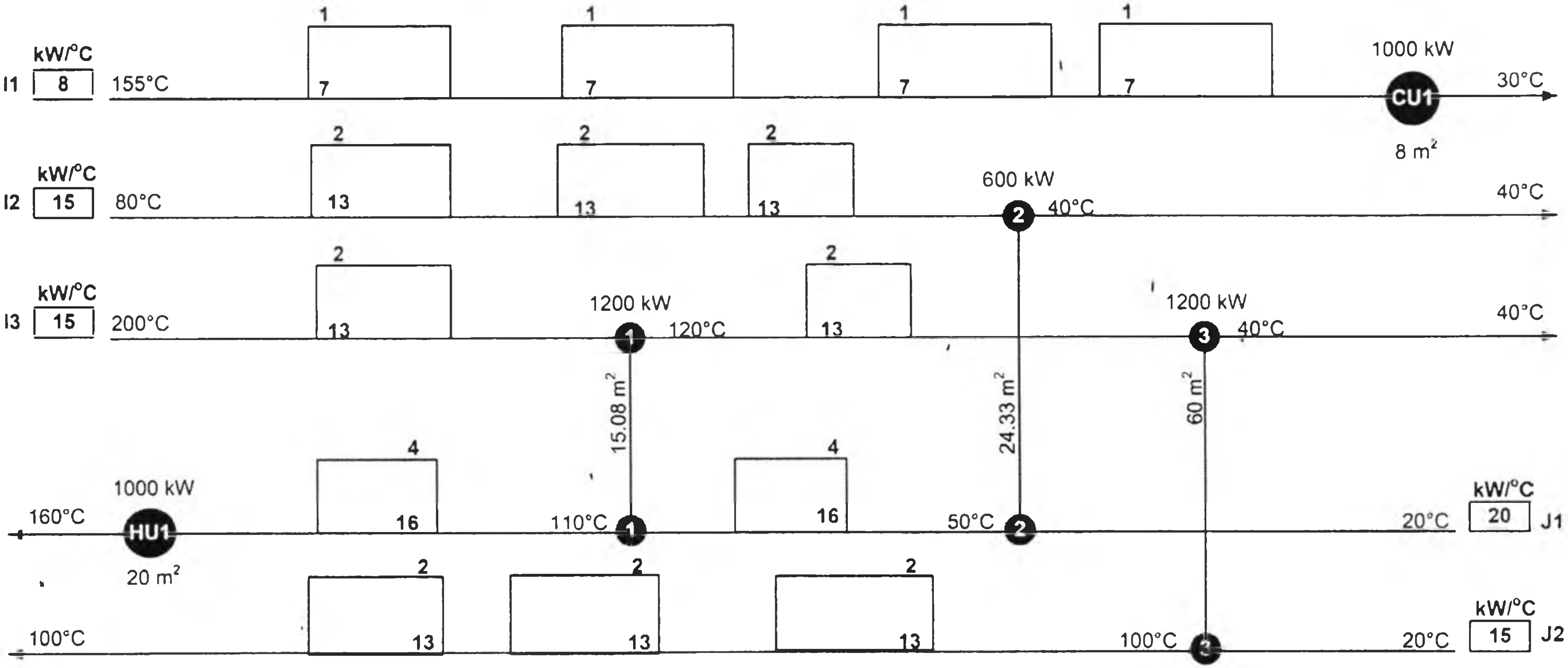
Total area (m^2)	3,142.5
Annualized utility cost	\$140,000
Investment cost	\$1,063,882
Total annualized cost	\$1,203,882

Figure 6.5 One of Heat Exchanger Configuration result from First MILP and First NLP of Example 2.



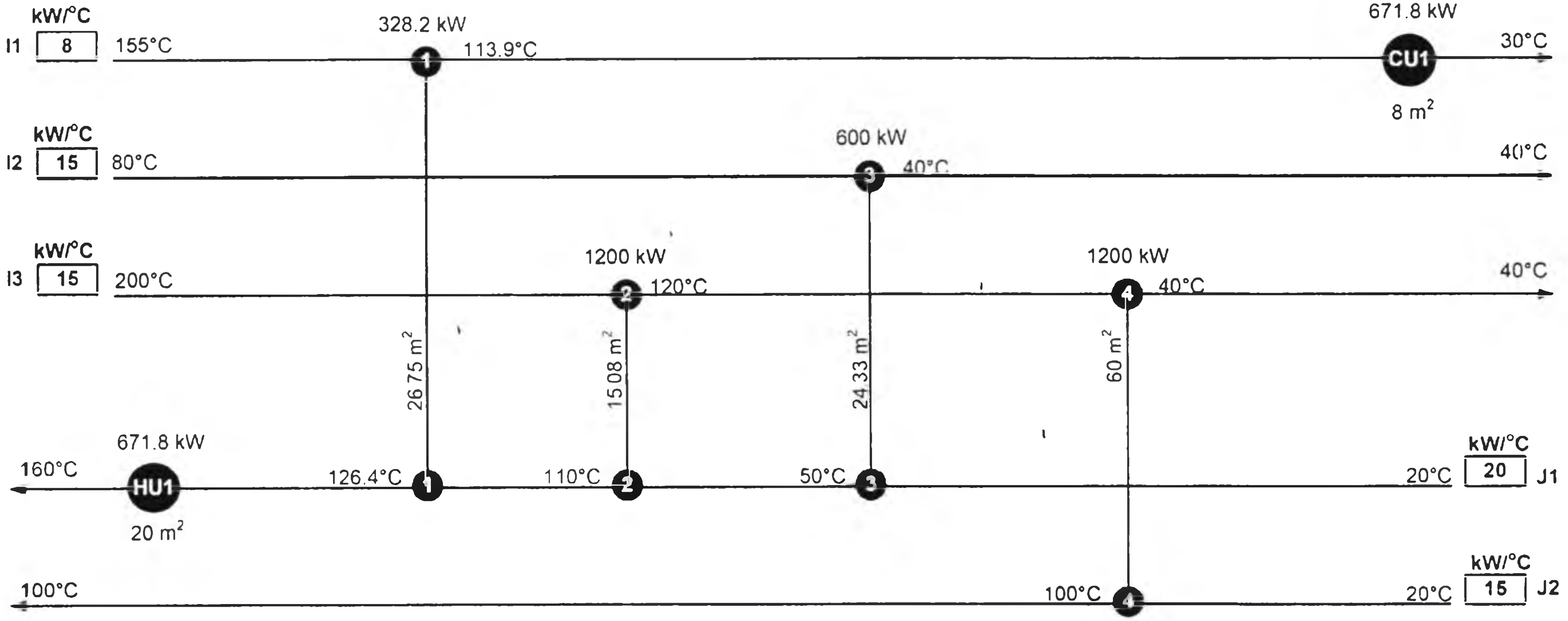
Total area (m^2)	3,142.5
Annualized utility cost	\$140,000
Investment cost	\$1,063,882
Total annualized cost	\$1,203,882

Figure 6.6 One of Heat Exchanger Configuration result from Second MILP of Example 2.



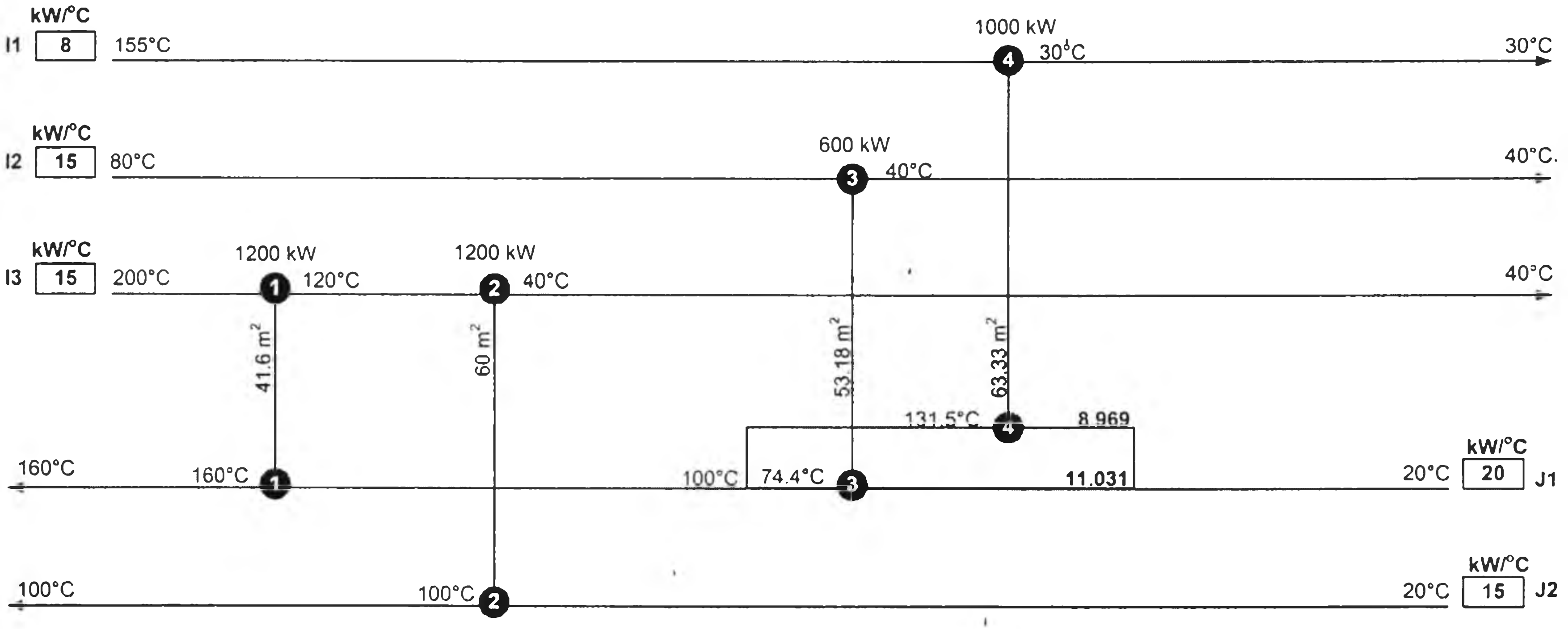
Total area (m^2)	127.5
Annualized utility cost	$140,000
Investment cost	$71,917
Total annualized cost	$211,917

Figure 6.7 One of Heat Exchanger Configuration result from Second NLP of Example 2.



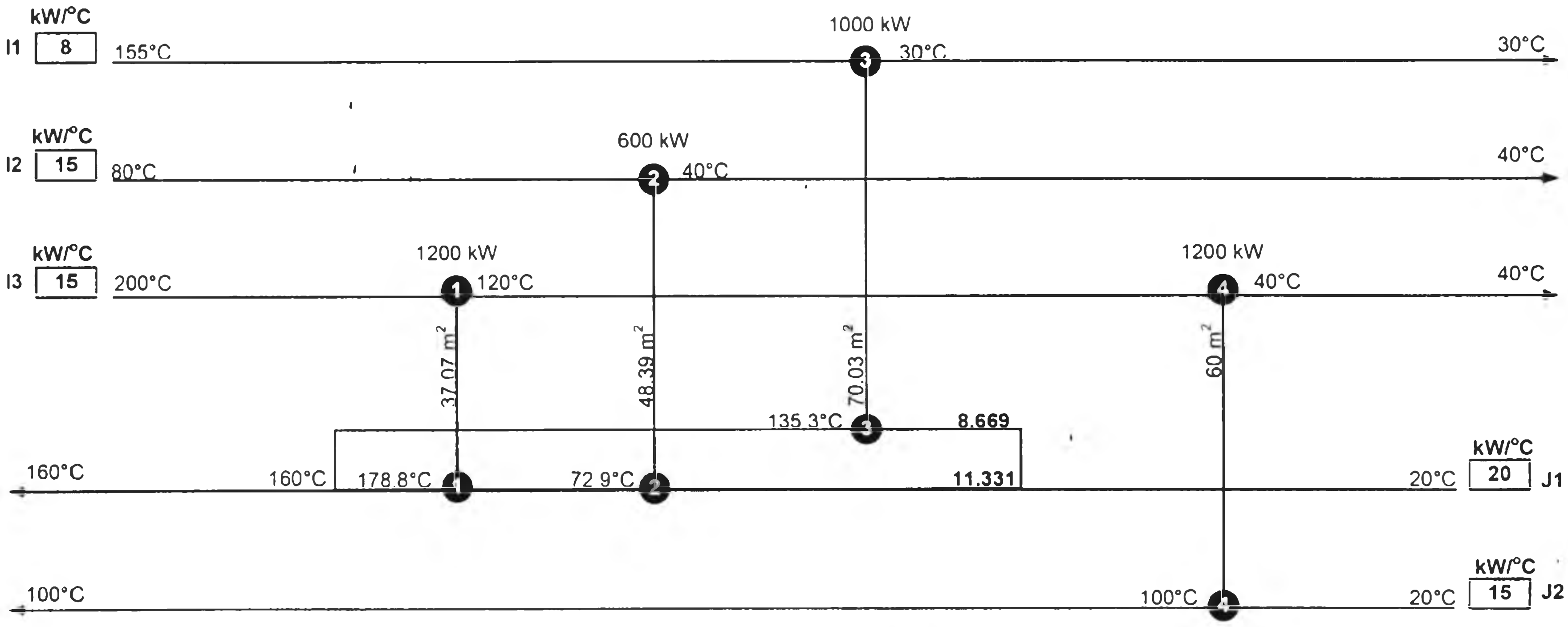
Total area (m^2)	154.1
Annualized utility cost	\$94,047
Investment cost	\$86,705
Total annualized cost	\$180,753

Figure 6.8 One of Heat Exchanger Configuration result from MINLP after solving each iteration of Example 2.



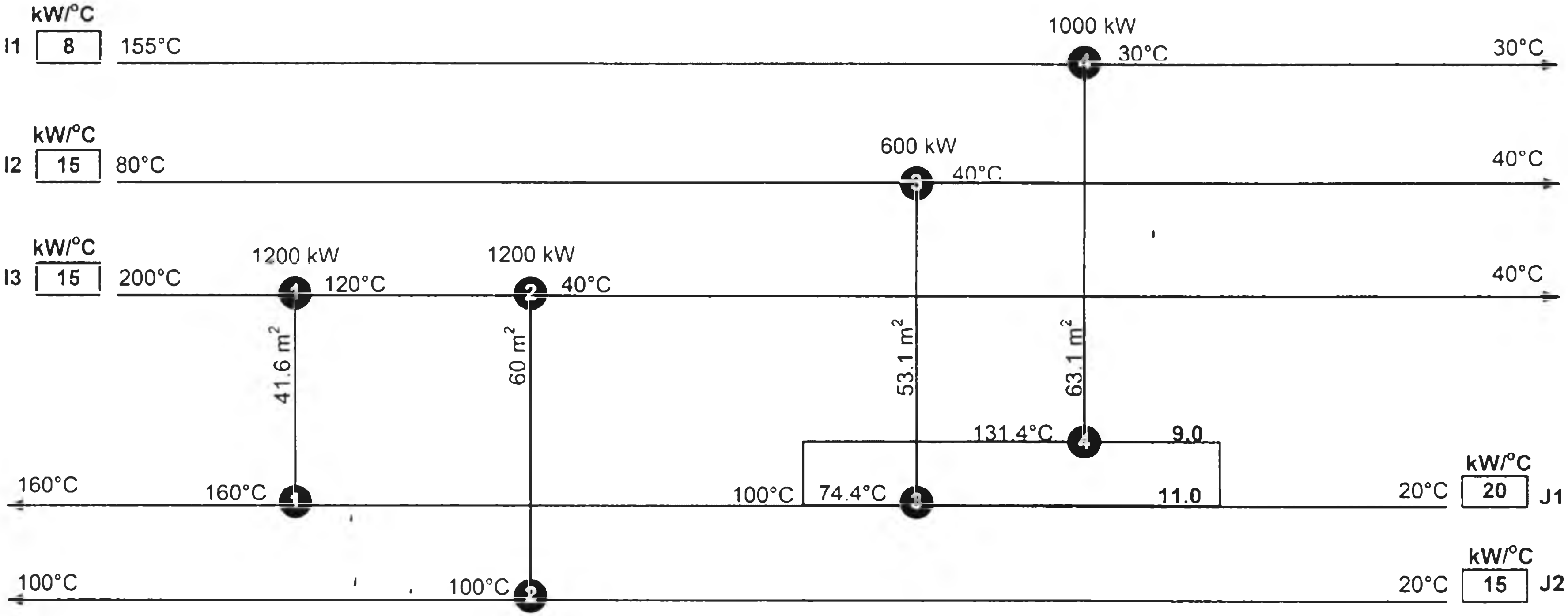
Total area (m^2)	218.1
Annualized utility cost	-
Investment cost	\$95,743
Total annualized cost	\$95,743

Figure 6.9 Final Heat Exchanger Configuration result of Example 2 after second iteration by applying a TAC^U constraint.



Total area (m^2)	215.5
Annualized utility cost	-
Investment cost	\$94,880
Total annualized cost	\$94,880

Figure 6.10 The best Heat Exchanger Configuration result from MINLP of Example 2 after third iteration by applying a TAC^U constraint of previous iteration (\$95,743).



Total area (m^2)	217.8
Annualized utility cost	-
Investment cost	$95,643
Total annualized cost	$95,643

Figure 6.11 Best Heat Exchanger Configuration result from Huang and Karimi (2012) of Example 2.

By Comparing between the First MILP and Second MILP (Figures 6.5 and 6.6 respectively), although the total area and TAC obtained from these two models are equal, the HEN configurations are slightly different. That is because solving MILP by using initial value can result in rearranging the result, which is used as initial value for the next model. Hence, good initial values can gradually tune the model to give solution to a desirable direction corresponding to each solving step.

We use the TAC ($180,753) as an upper bound to solve second iteration and it obtains a HEN with TAC of $95,743 (Figure 6.9). Finally, from this strategy, we obtained the best result of this problem (Figure 6.10) with a TAC of $94,880. The result comparison of our work and literature are shown in Table 6.4. The HEN configuration are different but our TAC is slighly better. This likely arises because of linear approximation technique in our objective function.

Table 6.4 Comparison of example 2 result of our model with literature

Comparison	Our model	Huang and Karimi (2012)	Björk and Westerlund (2002)
Total area(m^2)	215.5	217.8	219.2
Number of HE	4	4	4
Annualized utility cost($)	-	-	-
Investment cost($)	94,880	95,643	96,001
TAC($)	94,880	95,643	96,001
Max CPU time(s)	3,353	3,600	96

From examples 1 and 2, the outlet temperature of hot and cold branch streams can be cooled or heated to a temperature lower or high than its parent stream's final temperature. As shown in example 1 (Figure 6.3), the outlet temperature if the HE3 sub-steam is 68.9°C which lower than its parent stream I1 with a final temperature of 77°C. Similarly, at the cold stream J1 of example 2

(Figure 6.10), the outlet temperature of HE1 sub streams (178.8°C) is higher than the final temperature of its parent stream J1 (160°C). In contrast, many previous HENs (Yee et al., 1990; Björk et al., 2002; Bergamini et al., 2008), models did not allow these case to happen. Huang and Karimi (2012) demonstrated that by limitating the sub-stream temperatures to be within the initial and final temperatures of their parent stream can miss other possibly HEN configurations. They proved effect of bounding temperature by proposing the method for synthesizing HEN with their non-isothermal mixing strategy by adding new variables. In this work, we bound all the temperature variables based on possible maximum and minimum temperature of the two matching parent streams. From this technique, all our temperature variables whether hot stream or cold stream can be located at any possible values.

6.1.3 Example 3

This example (Table 6.5) was also taken from Björk and Westerlund (2002). It includes two hot and four cold process streams with one hot and one cold utility. The exchanger cost ($) is 8,000+50(Area)$^{0.75}$. Björk and Westerlund (2002) reported their best model with six HEs, one heater, one cooler, and the best TAC of $139,083 with thier non-isothermal strategy. Their TAC is lower than the $140,367 reported by Bergamini et al.(2007) as the global optimal solution from their strategy while Björk and Westerlund (2002) did not report their HEN configuration. Also, Huang and Karimi (2012) model obtained a lower TAC of $128,169 (Figure 6.17). Comparing with our model, the TAC is about $123,637 (Figure 6.16).

Our solving strategy of this problem started with guessing initial value of branch flow. After changing initial value when first iteration is infeasible, the first feasible result TAC is $123,637. Then, this TAC was used as upper bound TAC for next solving iteration. After solving by using upper bound TAC of $123,637, the final result is infeasible although changing initial point based on the aforementioned solving strategy. We then conclude that the final result with a TAC of $123,637 is the best result. Figures 6.11 to 6.15 are the results of each step to the final result.

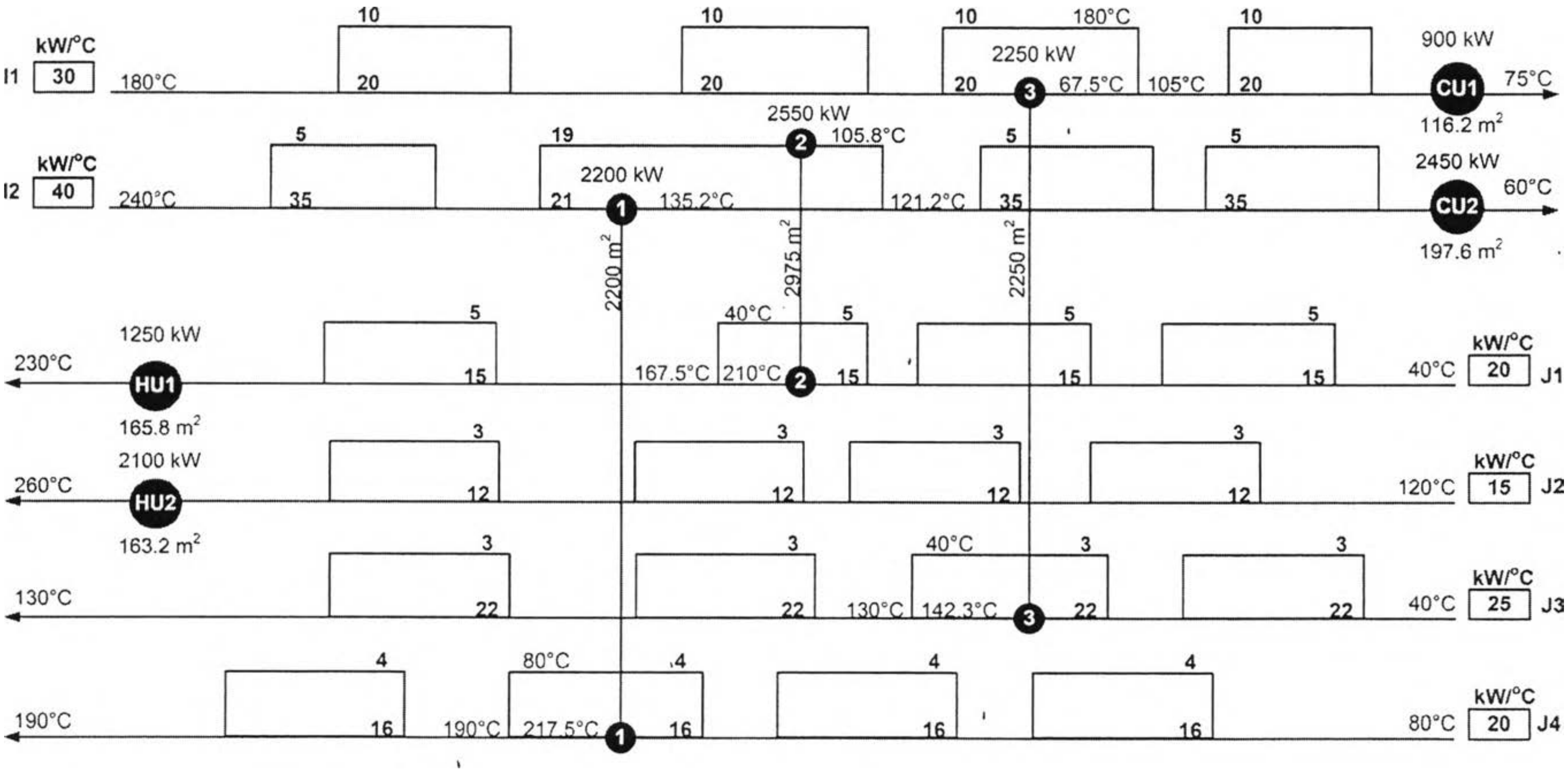
Comparison the result between solving First MILP (Figure 6.12) and NLP (Figure 6.13), the heat (HU1) and cold (CU2) utilities are decreased while heat exchange value (HE2) increases. That is because the objective function of First NLP is to minimize utility consumption while branch flow variable are not fixed.

Table 6.5 Example 3 data

Stream	TIN(°C)	TOUT(°C)	h(kW/m^2-°C)	F(kW/°C)	Cost($/kW-yr)
I1	180	75	2	30	-
I2	240	60	2	40	-
J1	40	230	1.5	20	-
J2	120	260	1.5	15	-
J3	40	130	2	25	-
J4	80	190	2	20	-
CU	25	25	1	-	20
HU	325	325	2	-	120

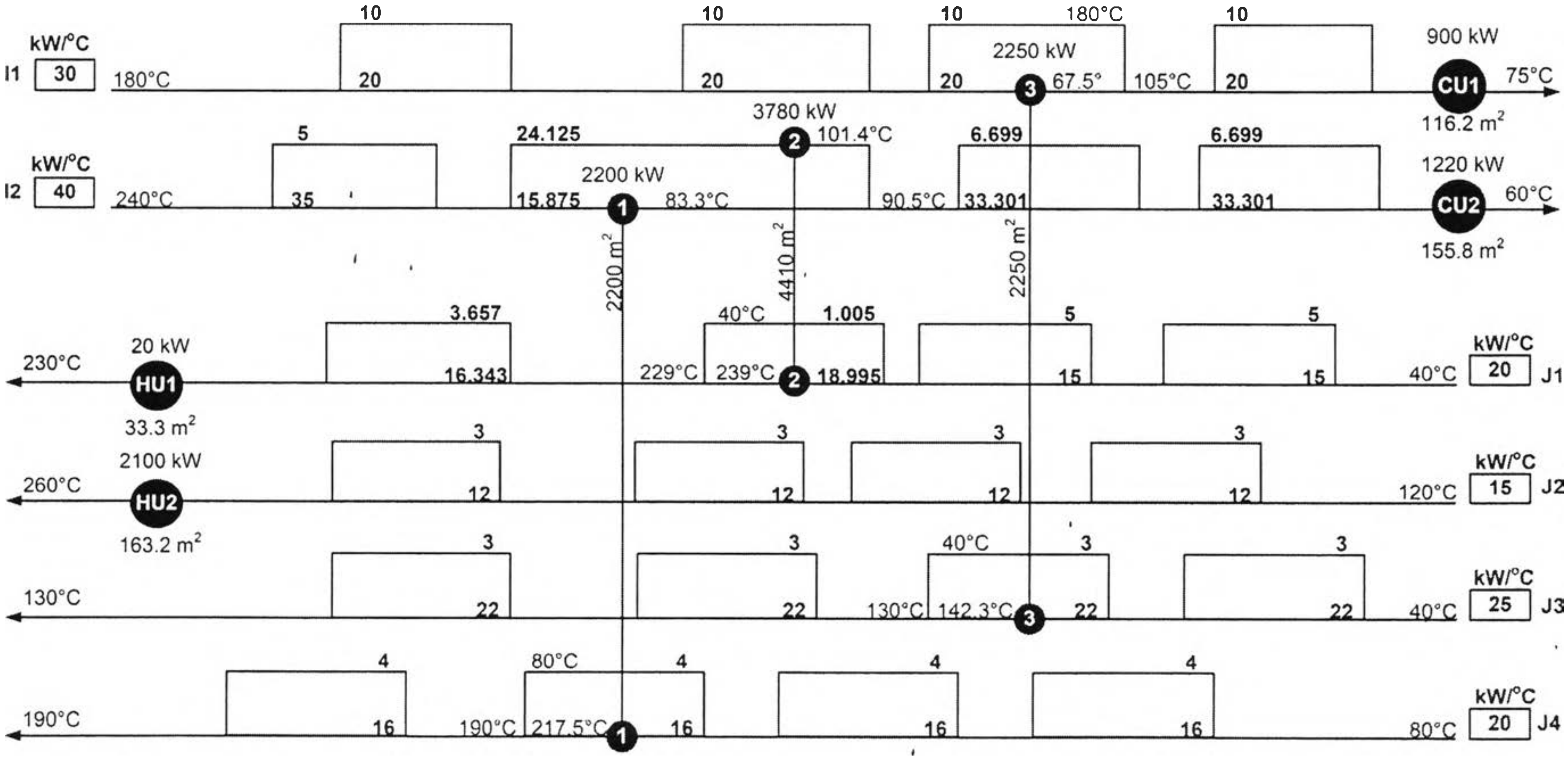
EMAT = 1°C

The results from Second MILP and Second NLP (Figures 6.14 and 6.15) illustrate that these are sub-optimal results compare with the final MINLP result. In contrast, to example 1 where, optimum solution was obtained after solving the Second NLP step. This is solely caused by the size of the problem. Solving a bigger size problem is more challenge since there are more alternative possibility results. Moreover, due to solving each step with fixing one variable to find the other can cause sub-optimal result of each step. Therefore, using all initial value from Second NLP for solving MINLP can cause the model fails because of sup-optimal result that occur from each step.



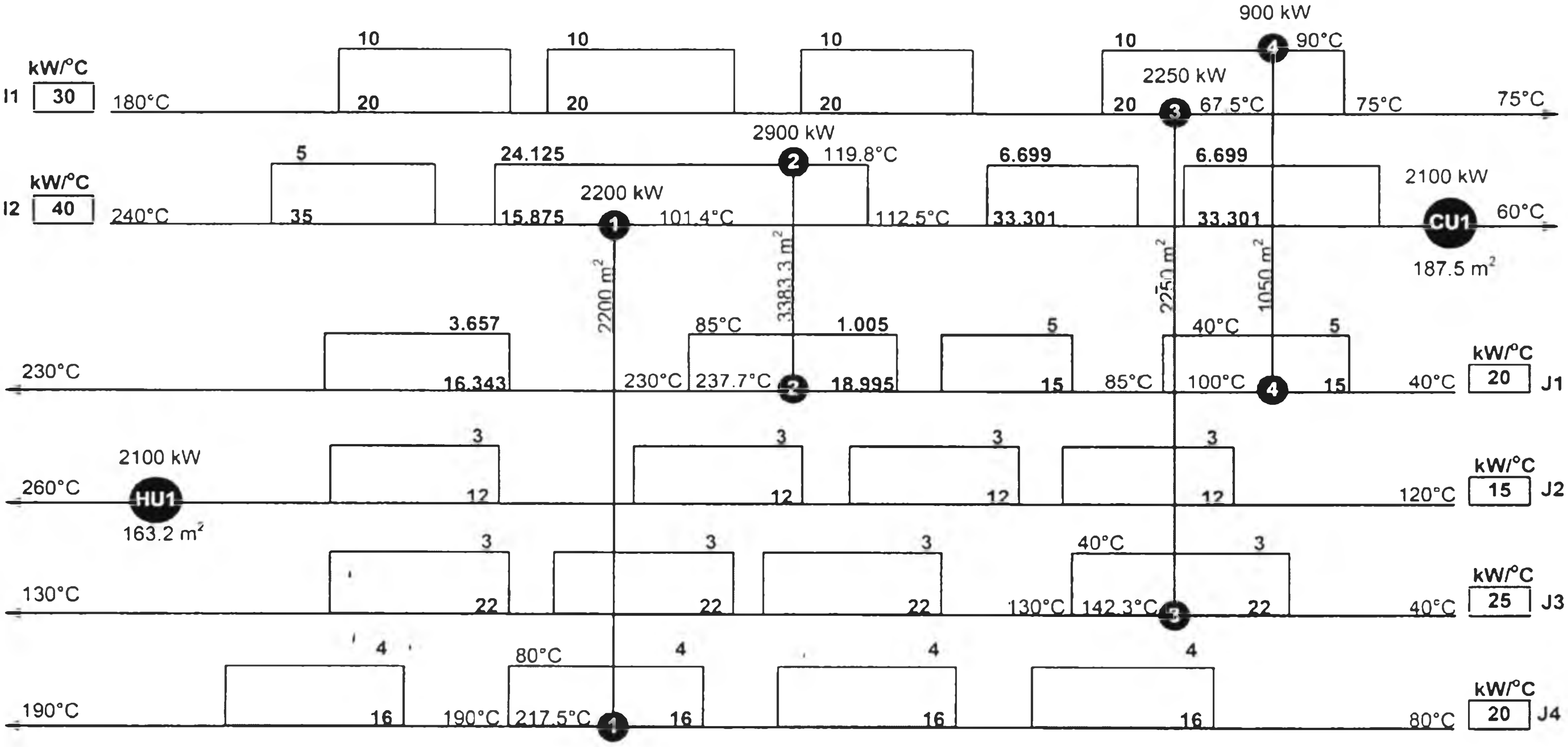
Total area (m^2)	8,067.7
Annualized utility cost	\$469,000
Investment cost	\$149,666
Total annualized cost	\$618,666

Figure 6.12 Heat Exchange Configuration result from First MILP of Example 3.



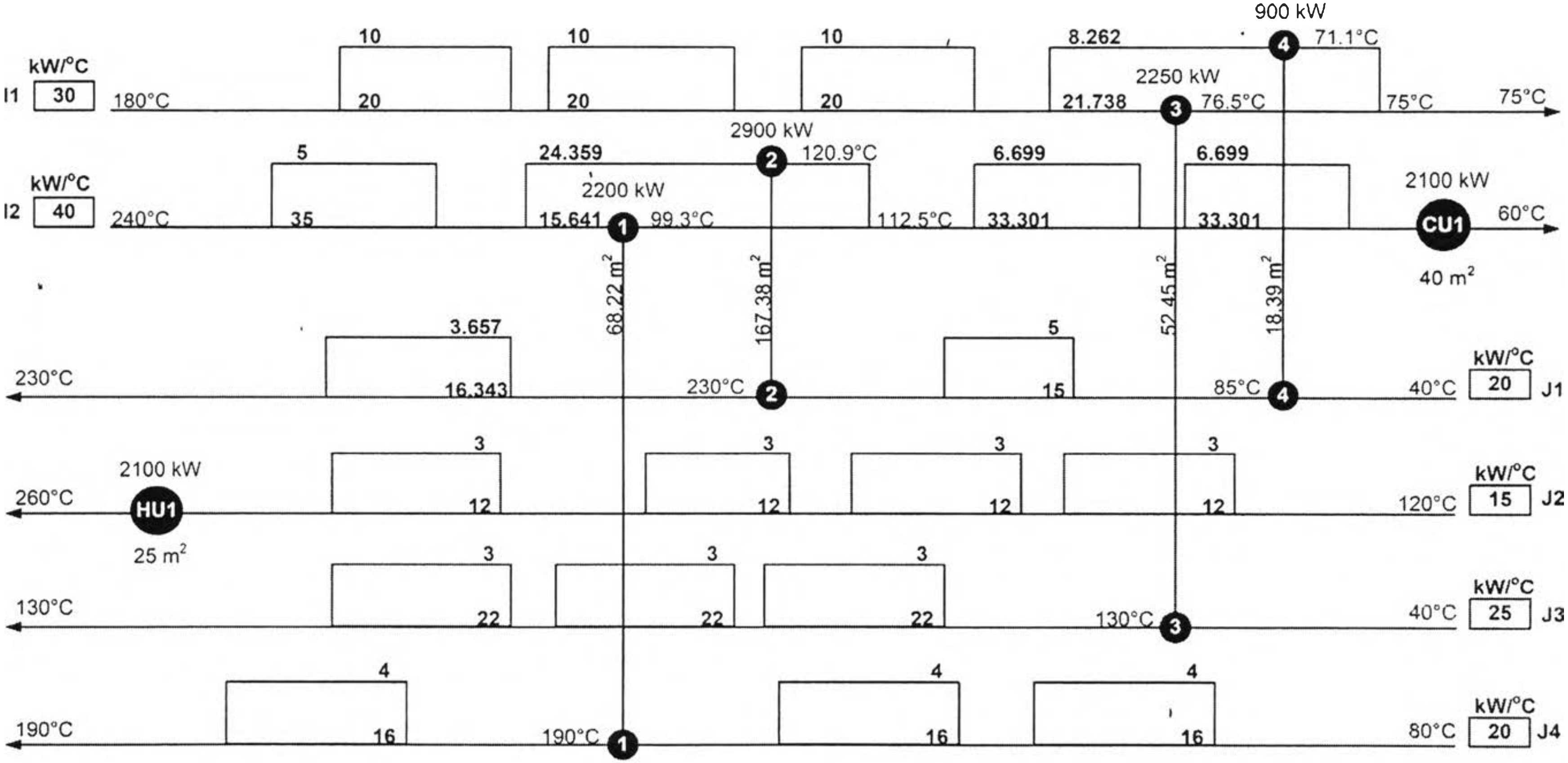
Total area (m^2)	7,328.4
Annualized utility cost	\$296,800
Investment cost	\$141,083
Total annualized cost	\$437,883

Figure 6.13 Heat Exchange Configuration result from First NLP of Example 3.



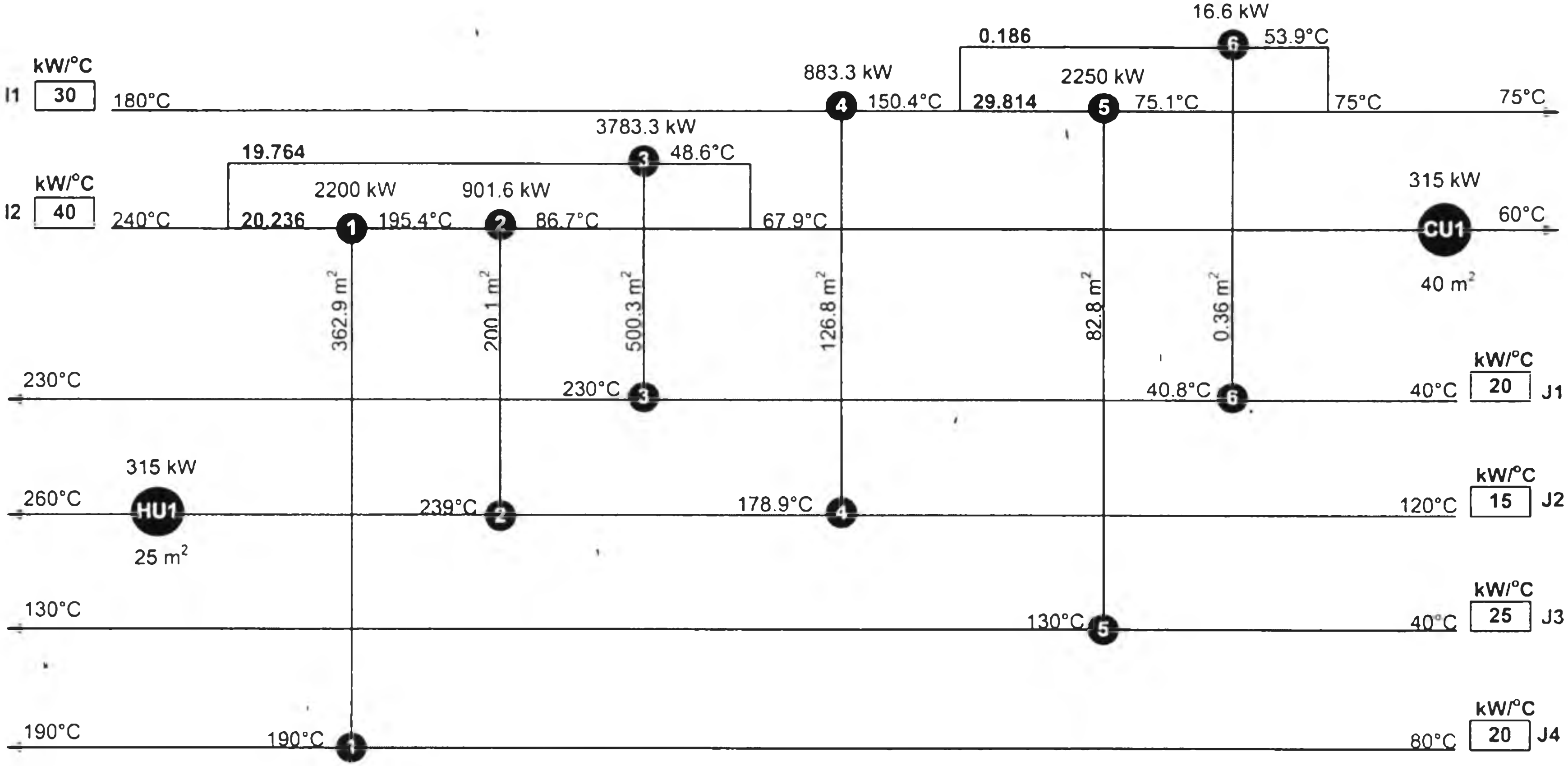
Total area (m^2)	9,234
Annualized utility cost	\$294,000
Investment cost	\$155,206
Total annualized cost	\$449,206

Figure 6.14 Heat Exchange Configuration result from Second MILP of Example 3.



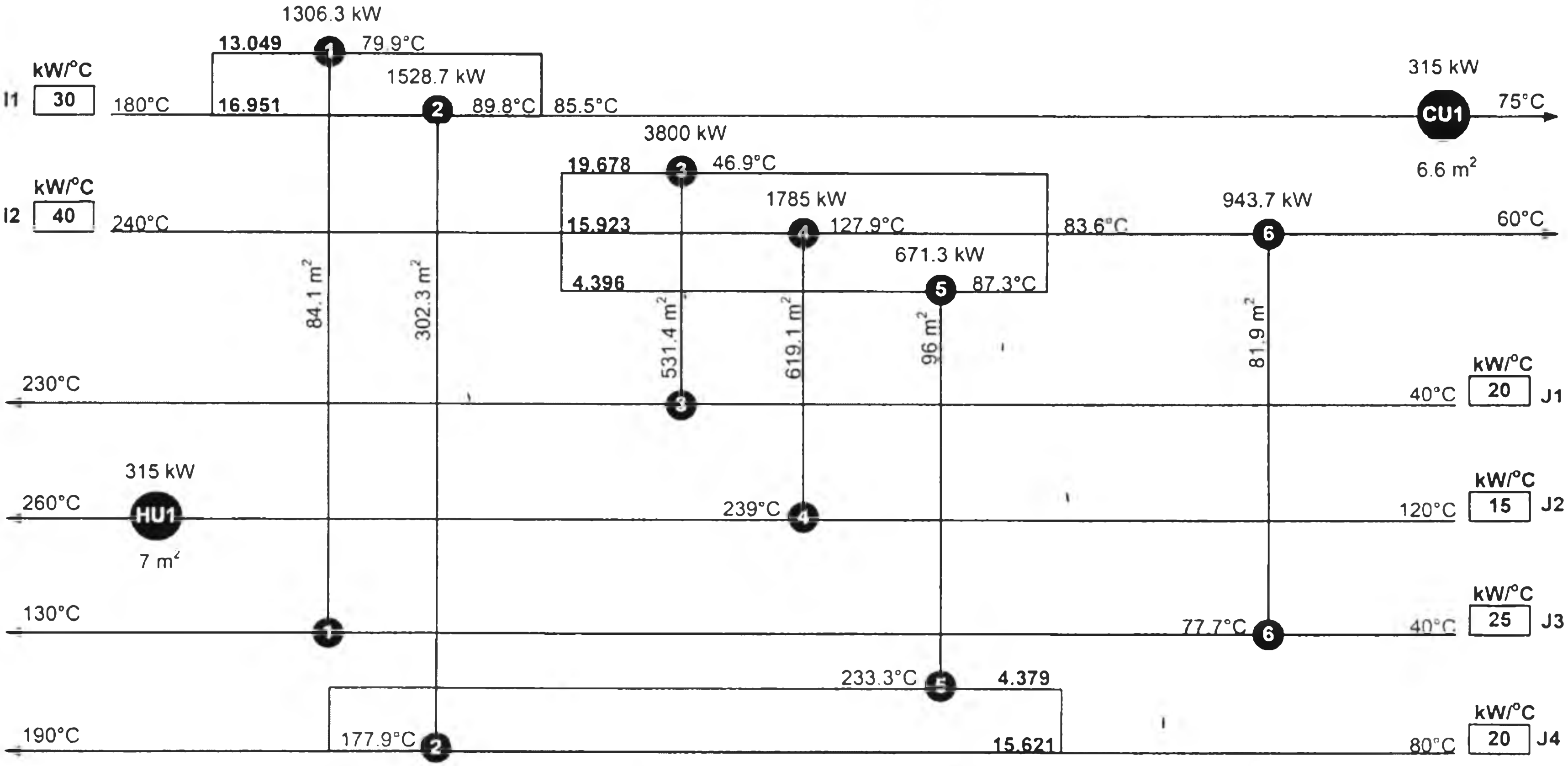
Total area (m^2)	371.4
Annualized utility cost	\$294,000
Investment cost	\$52,312
Total annualized cost	\$346,312

Figure 6.15 Heat Exchange Configuration result from Second NLP of Example 3.



Total area (m^2)	1,338.3
Annualized utility cost	\$44,100
Investment cost	\$79,537
Total annualized cost	\$123,637

Figure 6.16 Final Heat Exchange Configuration result from MINLP of Example 3.



Total area (m^2)	1,728.4
Annualized utility cost	\$44,100
Investment cost	\$84,069
Total annualized cost	\$128,169

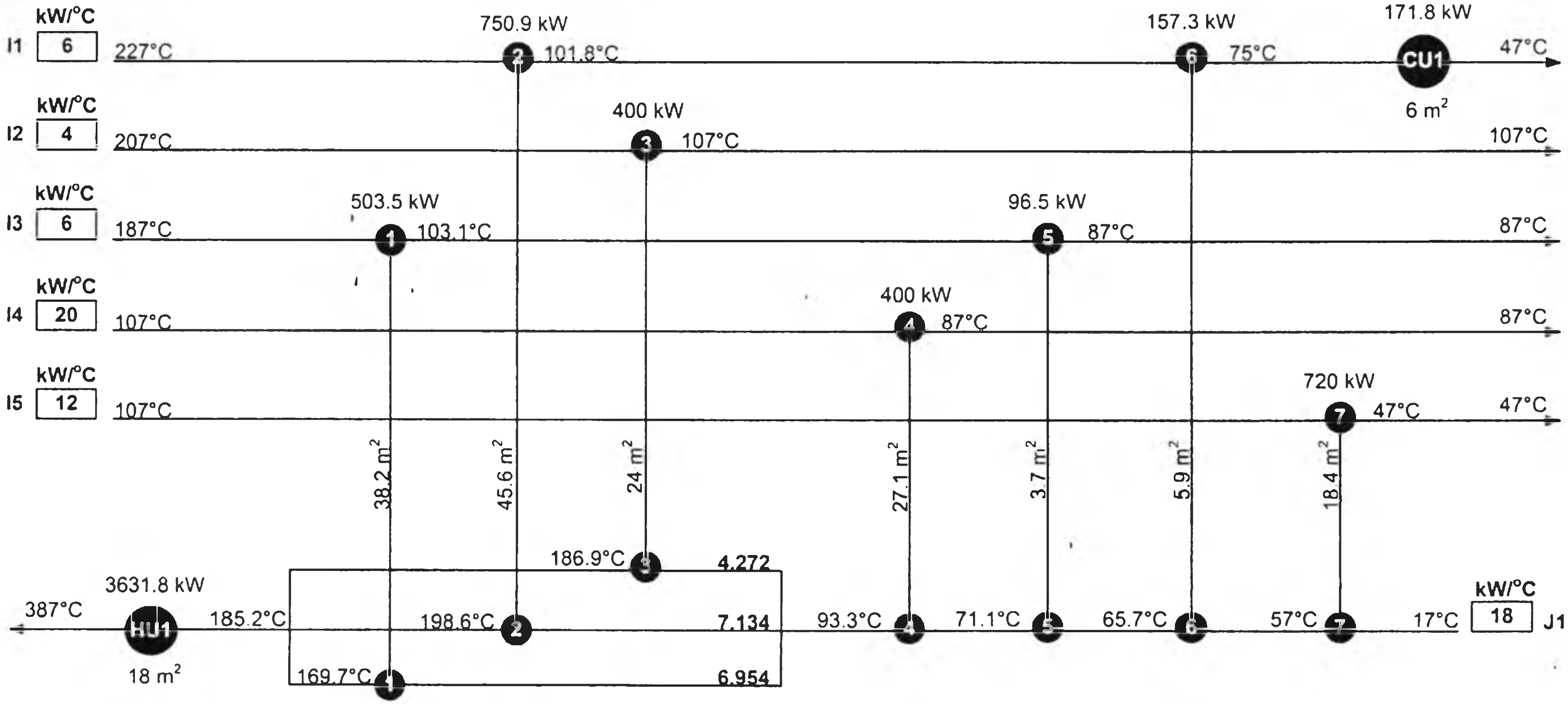
Figure 6.17 Best Heat Exchange Configuration result from Huang and Karimi (2012) for Example 3.

Table 6.6 Comparison of example 2 result of our model with literature

Comparison	Our model	Huang and Karimi (2012)	Bergamini et al. (2007)
Total area(m^2)	1,338.3	1728.4	1190.3
Number of HE	8	8	10
Annualized utility cost($)	44,100	44,100	44,100
Investment cost($)	79,537	84,069	96,267
TAC($)	123,637	128,169	140,367
Max CPU time(s)	19,108	7,200	Not report

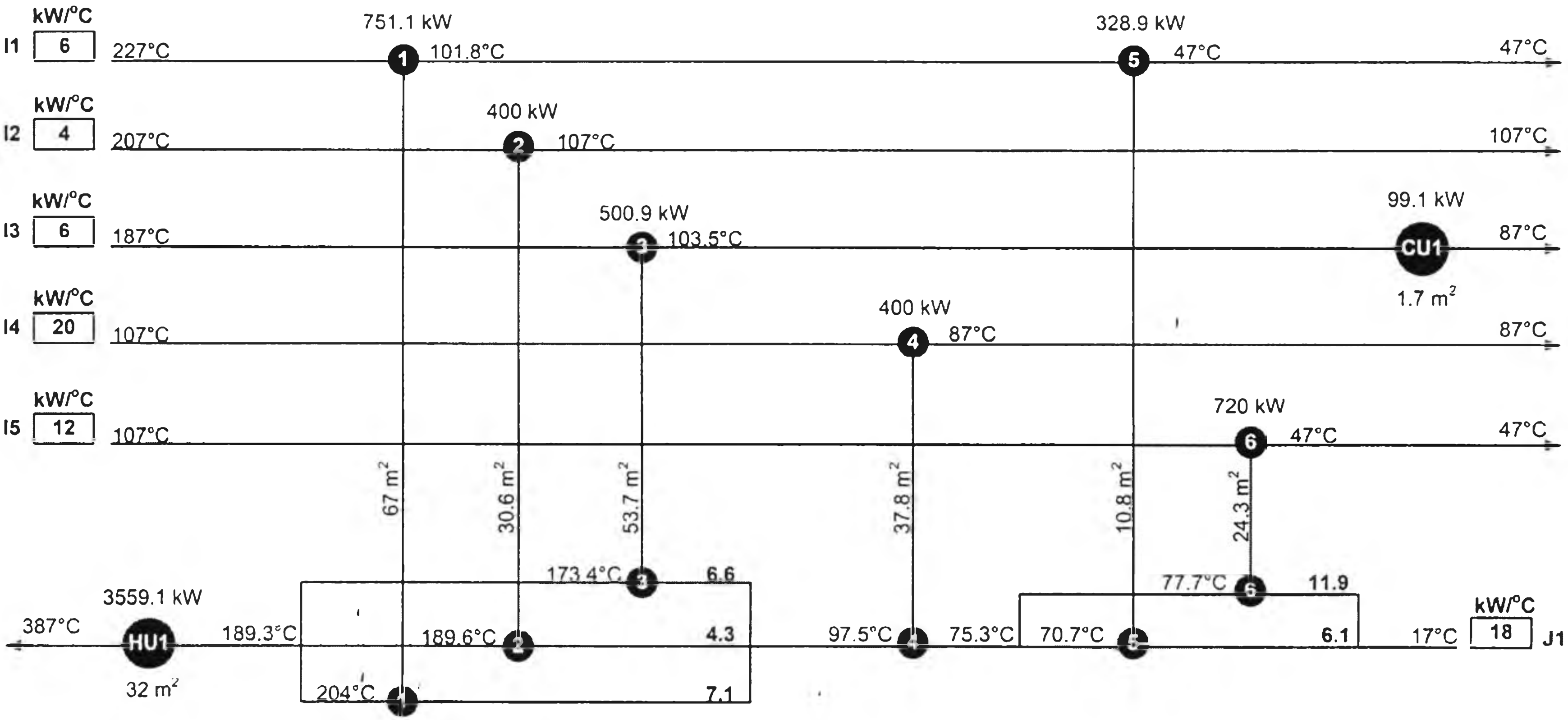
6.1.4 Example 4

This example (Table 6.7) was originally taken from Yee and Grssmann (1990). It involves five hot (I1-I5) and one cold (J1) process streams with one hot and one cold utility. A main propose of this example is to compare the isotheraml and non-isothermal strategies. The exchanger cost is 1200(Area)$^{0 6}$ \$/m^2. Huang and Karimi (2012) reported their best model with six HEs, one heater, one cooler, and the best TAC of $571,657 (Figure 6.18) while the best result reported (Figure 6.20) by Khorasany and Fesanghary (2009) was $572,476. These results are lower than the two solutions that reported by Yee and Grossmann (1990) ($576,640 via the isothermal strategy and $575,595 by the sequential approach). Comparing with our model, the HEN configuration consists of seven HEs, one heater, and one cooler. the our best TAC is of $565,704 (Figure 6.18).



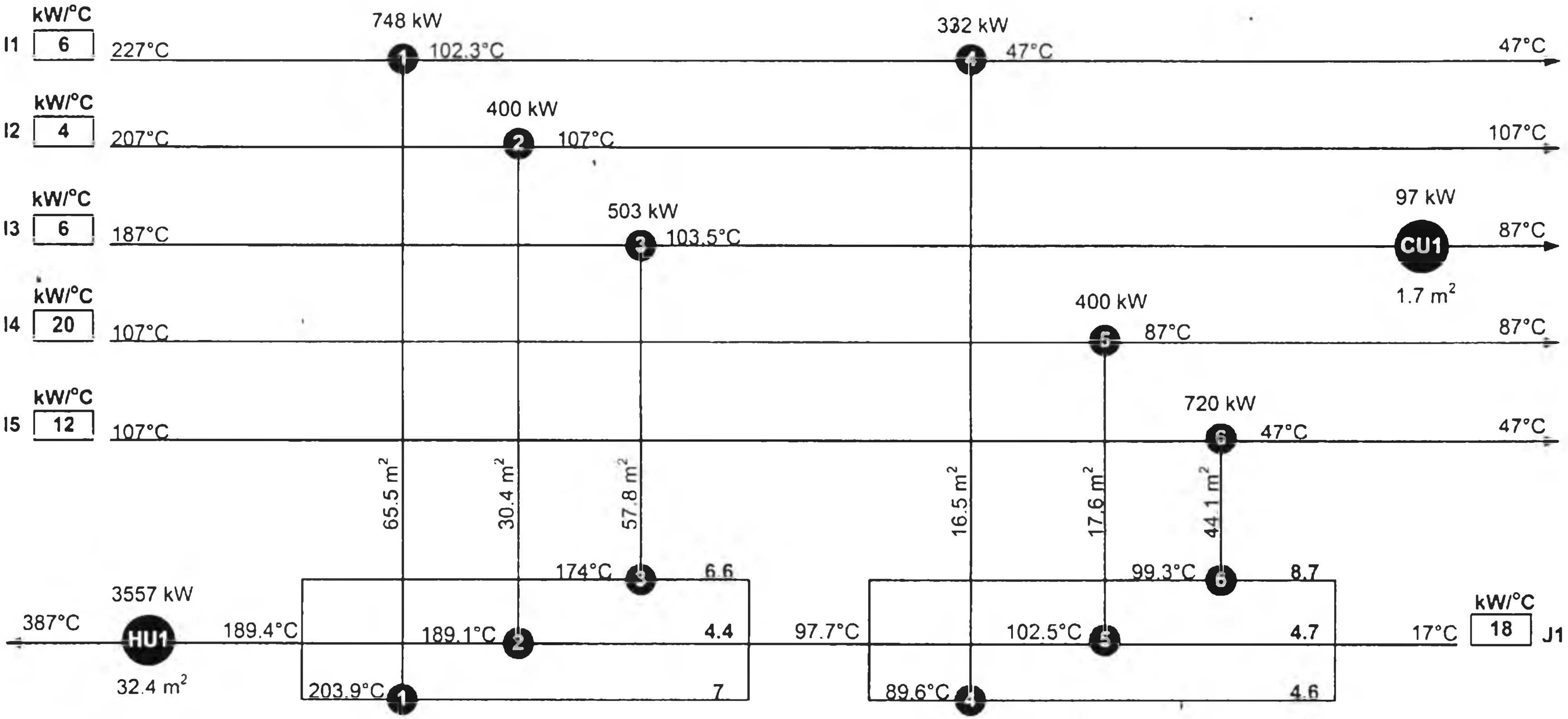
Total area (m^2)	186.9
Annualized utility cost	\$510,171
Investment cost	\$55,533
Total annualized cost	\$565,704

Figure 6.18 Final Heat Exchange Configuration result from MINLP of Example 4.



Total area (m^2)	257.9
Annualized utility cost	\$499,263
Investment cost	\$72,394
Total annualized cost	\$571,657

Figure 6.19 Best Heat Exchange Configuration result from Huang and Karimi (2012) for Example 4.



Total area (m^2)	265.9
Annualized utility cost	\$498,950
Investment cost	\$73,526
Total annualized cost	\$572,476

Figure 6.20 Best Heat Exchange Configuration result from Khorasany and Fesanghary (2009) for Example 4.

Table 6.7 Example 4 data

Stream	TIN(°C)	TOUT(°C)	h(kW/m^2-°C)	F(kW/°C)	Cost($/kW-yr)
I1	227	47	2	6	-
I2	207	107	2	4	-
I3	187	87	2	6	-
I4	107	87	2	20	-
I5	107	47	2	12	-
J1	17	387	2	18	-
CU	27	47	2	-	10
HU	427	427	2	-	140

EMAT = 5°C

This example consists only one large cold steam, giving a high possibility of splitting the cold stream. Therefore, the outlet temperature of sub-stream can affect the HEN configuration significanly (Huang *et al.*, 2012). Our solution uses higher number of HEs and annualized utility consumption, but lower heat exchanger area.

Table 6.8 Comparison of example 4 result of our model with literature

Comparison	Our model	Huang and Karimi (2012)	Khorasany and Fesanghary (2009)
Total area(m^2)	186.9	257.9	265.9
Number of HE	9	8	8
Annualized utility cost($)	510,171	499,263	498,950
Investment cost($)	55,533	72,394	73,526
TAC($)	565,704	571,657	572,476
Max CPU time(s)	417	3600	930

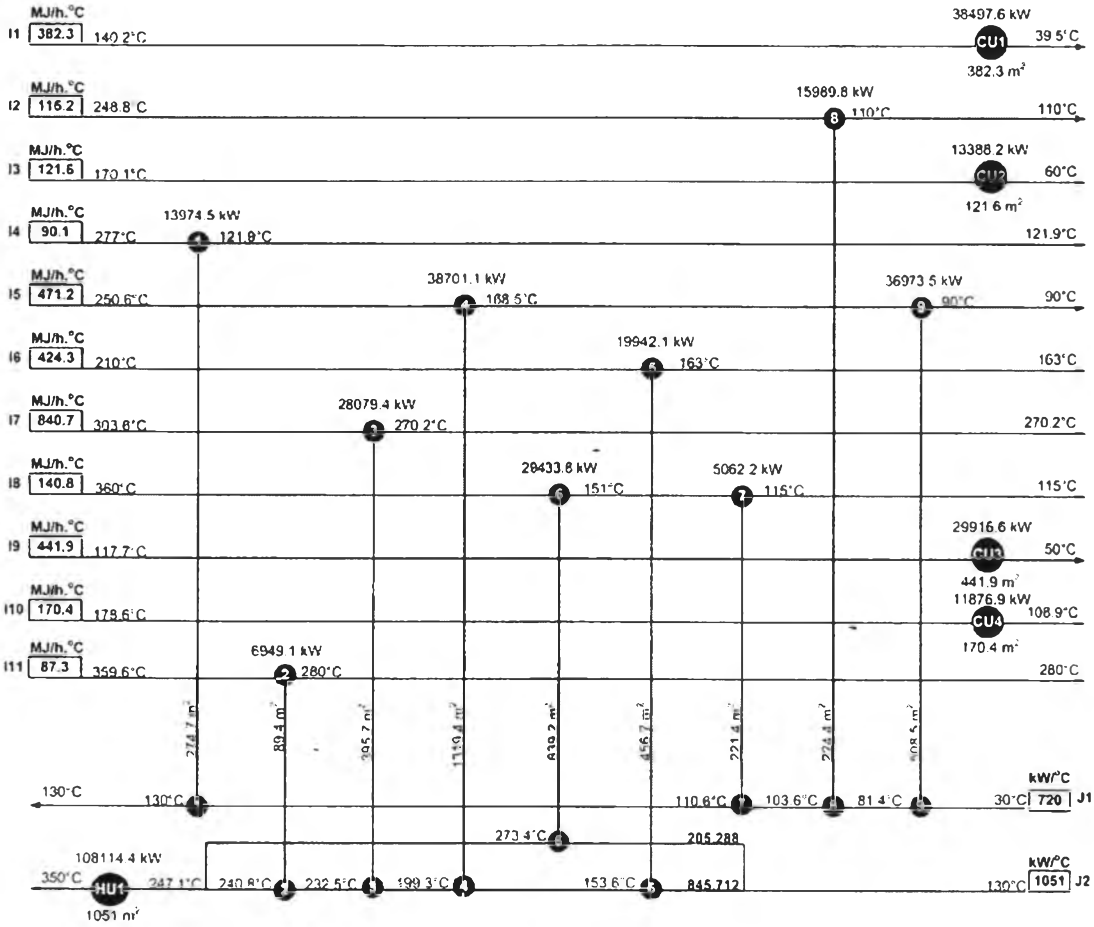
6.2 Example from Real Industrial Process

This example consists of eleven hot and two cold process streams with one hot and one cold utility. The data for the example is presented in Table 6.10. the fixed cost of units is 127,129$/unit, and the area cost coefficient is 271.2 $/m^2. Oue model yields nine HEs, one heater, four cooler, and the best TAC of $6,751,330 (Figure 6.21) and the maximum PC time is 25,775 s The main propose of this example is to compare the effect of problem size with computational time.

Table 6.9 Example from real industrial process

Stream	TIN(°C)	TOUT(°C)	h(kW/m^2-°C)	F(kW/°C)	Cost($/kW-yr)
I1	140.2	39.5	2	382.3	-
I2	248.8	110	2	115.2	-
I3	170.1	60	2	121.6	-
I4	277	121.9	2	90.1	-
I5	250.6	90	2	471.2	-
I6	210	163	2	424.3	-
I7	303.6	270.2	2	840.7	-
I8	360	115	2	140.8	-
I9	117.7	50	2	441.9	-
I10	178.6	108.9	2	170.4	-
I11	359.6	280	2	87.3	-
J1	30	130	2	720	-
J2	130	350	2	1051	-
CU	25	25	2	-	2.78
HU	370	370	2	-	27.78

EMAT = 10 °C



Total area (m^2)	6,296.7
Annualized utility cost	\$4,971,524
Investment cost	\$1,779,806
Total annualized cost	\$6,751,330

Figure 6.21 Final Heat Exchanger configuration from MINLP of Example from real industrial process.