4 Results And Discussion

4.1 Example 1

Example 1 is the base-case of HEN with two hot and three cold streams and four heat exchangers. The annual hot and cold utility consumption of the existing network is 11,275 kW and 9,267 kW, respectively as shown composite curves of Figure 4.2, corresponding to heat recovery approach temperature (HRAT) = 27 °C and exchanger minimum approach temperature (EMAT) = 7.7 °C. Information of base-case is shown in Figure 4.1 and Table 4.1 and 4.2.

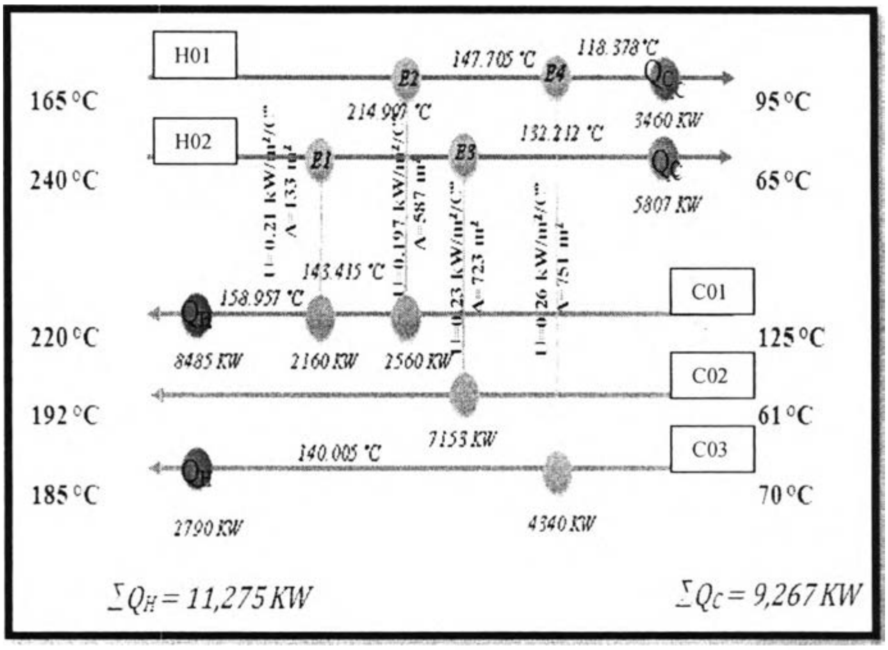

Figure 4.1 Grid diagram of example 1 in base case *(EMAT = 7.7).*

Table 4.1 Information of base case of example 1

UNIT	Heat Exchanger Area(m^2)	Heat Load (kW)
E1	133	2160
E2	587	2560
E3	723	7153
E4	751	4340

(Information from above table was got from eq.20)

Table 4.2 Data for two hot/three cold stream problem of example 1

Stream	TIN(°C)	TOUT(°C)	FCp(kW/°C)	h(kW/m^2°C)
H1	165	95	148	0.45
H2	240	65	86.4	0.55
C1	125	220	139	0.35
C2	61	192	54.6	0.40
C3	70	185	62	0.64

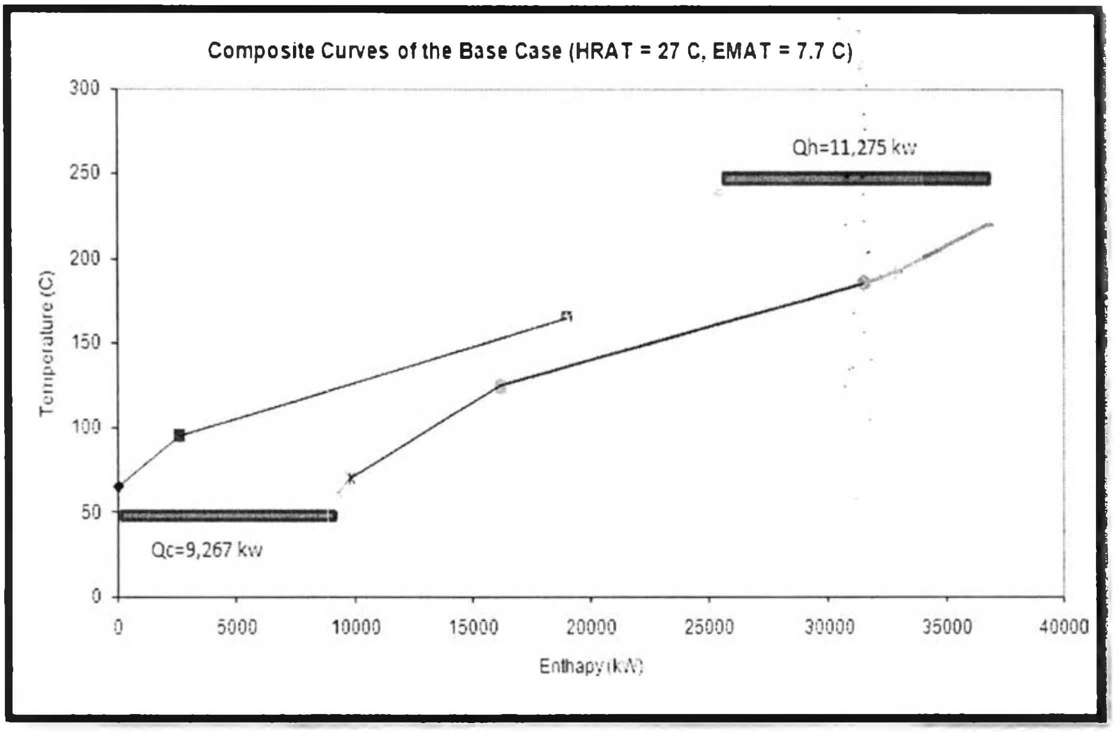

Figure 4.2 Composite curves of the base-case HEN.

In this example, the result has been showed in retrofit method. Furthermore retrofit design has relocation of concept 1 and concept 2 to compare cost for optimum point or the most profit. Figure 4.3 indicated maximum profit point and final retrofit network will be created at this point.

Condition for solution

1. No splitting of hot or cold stream by equation as follow:

$\sum_j Z_{ijk} \leq 1$

(eq.21)

$\sum_i Z_{ijk} \leq 1$

(eq.22)

*** Z_{ijk} *is binary variable*

2. EMAT is 7.7 K
3. *Cost (\$)* = $6,600+670(Area)^{0.83}$ for all new exchanger, *Area in* m^2 (eq.23)
4. *Cost (\$)* = $670(\Delta Area)^{0.83}$ for addition of area in existing heat exchanger (eq.24)
5. No removal heat exchanger area cost
6. Life time = 3 year and % annual interest = 0
7. Hot utility cost = 120 \$/kW/year
8. Cold utility cost = 20 \$/kW/year

4.1.1 Retrofit with relocation concept1 of Example 1

Plot graph between profit(\$) and hot or cold utility as shown in Figure 4.3. The profit of the retrofit case is calculated by eq.25:

Profit = Utility saving cost – New exchanger cost – Added area cost (eq.25)

The base-case HEN is retrofitted by using retrofit model of GAMS with MILP (Mixed Integer Linear Programming) and the relocation program with concept 1 and 2 using Visual C++. The retrofitted HEN at different HRAT is generated by the retrofit model. Applying the program of the relocation concept 1, the profit of retrofitted HEN at different HRAT (or hot utility) is plotted as shown in Figure 4.3. And the optimal retrofitted HEN with relocation concept 1 is found as shown in figure 4.4, giving the maximum profit of \$1,000,000 in 2.5 years.

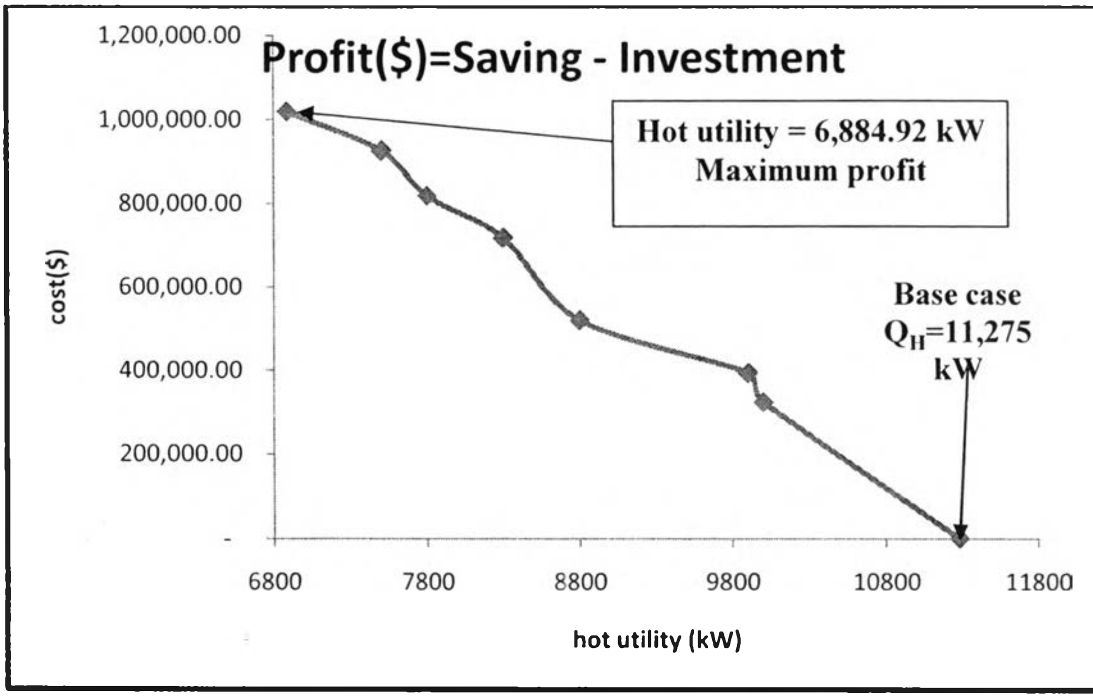

Figure 4.3 Total profit as a function of hot utility in concept 1 of example 1.

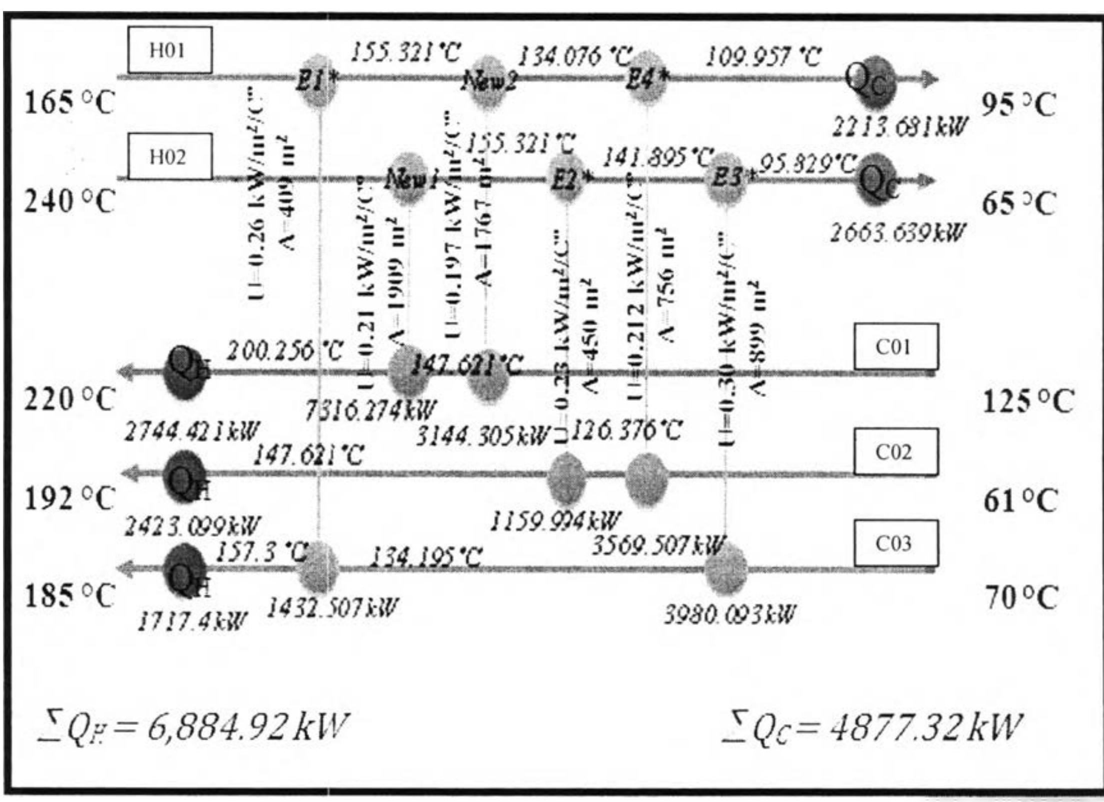

Figure 4.4 Grid diagram of example 1 in retrofit design in concept 1
(EMAT = 7.7 °C).

The optimal retrofit case consumes hot and cold utilities of 6,885 and 4,877 kw, respectively, with HRAT = 7.7 °C, as shown in the composite curves of Figure 4.5

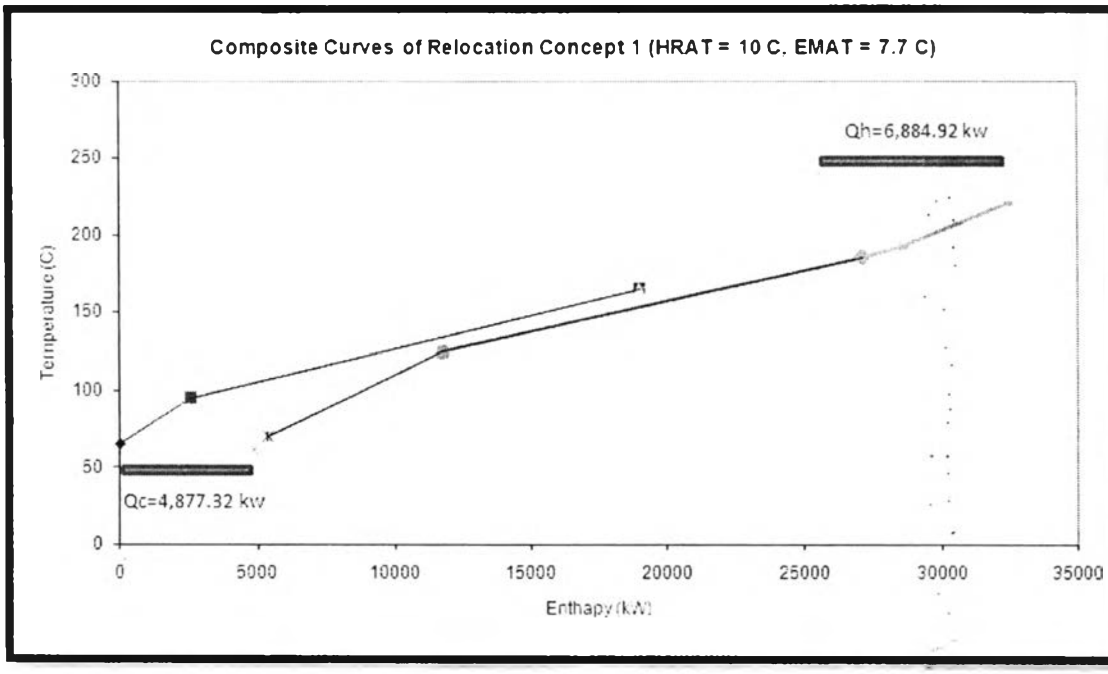

Figure 4.5 Composite curves of the optimal retrofit case with relocation concept 1.

The relocated and new exchangers of the retrofit case with relocation concept 1 is shown in Table 4.3.

Table 4.3 Result of retrofit design in concept 1 of example 1

UNIT	Heat Exchanger Area (m^2)	Heat Load (kW)	Area Cost $
E1*=E1+276	**408**	**1,432.507**	**71,126.156**
E2*=E2-138	**449**	**1,159.994**	-
E3*E3+175	**901**	**3,980.093**	**48,730**
E4*=E4+14	**766**	**3,569.507**	**5,989.09**
New1	**1,767**	**7,316.274**	**338,709.38**
New2	**1,909**	**3,144.305**	**360,714.51**
	Σ = 6,200		**Σ = 825,269.136**

*** *This table doesn't include cost for moving, demolishing.*

4.1.2 Retrofit with relocation concept 2 of Example 1

For the retrofit case with relocation concept 2, the retrofitted HEN at different HRAT is generated by the retrofit model. Applying the program of the relocation concept 2, the profit of retrofitted HEN at different HRAT (or hot utility) is plotted as shown in Figure 4.6. And the optimal retrofitted HEN with relocation concept 2 is found as shown in Figure 4.7, giving the maximum profit of $900,000 in 2.5 years.

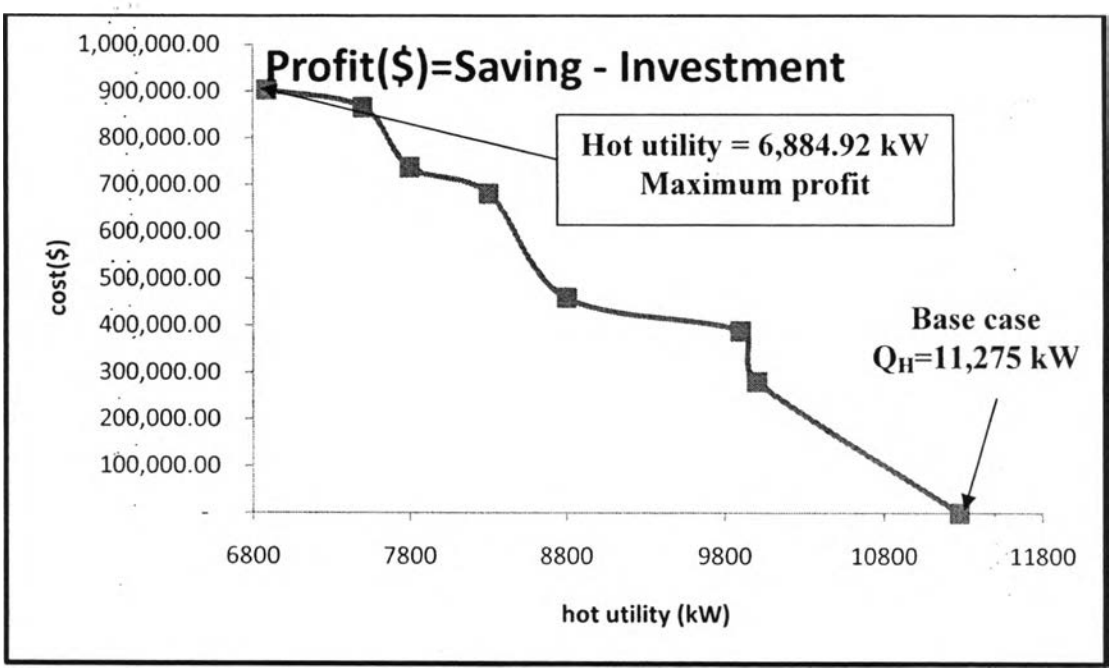

Figure 4.6 Total profit as a function of hot utility in concept 2 of example 1.

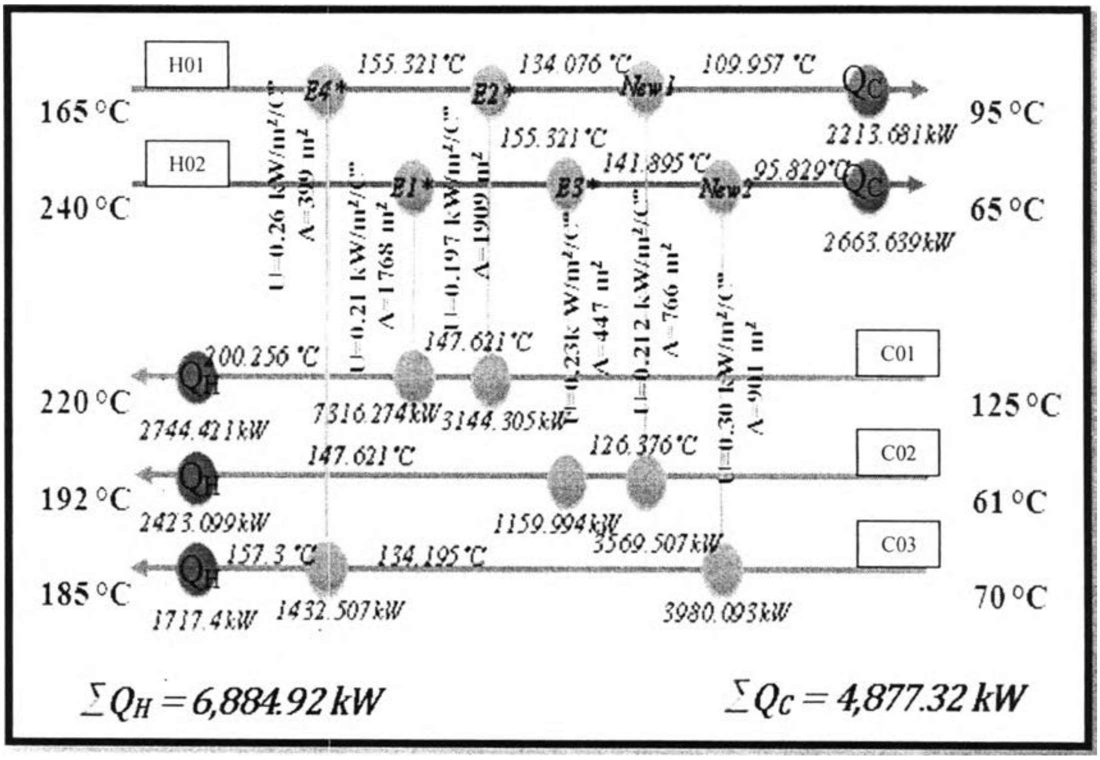

Figure 4.7 Grid diagram of example 1 in retrofit design in concept 2

(EMAT = 7.7 °C).

The optimal retrofit case consumes hot and cold utilities of 6,885 and 4,877 kw, respectively, with HRAT = 7.7 °C, as shown in the composite curves of Figure 4.8.

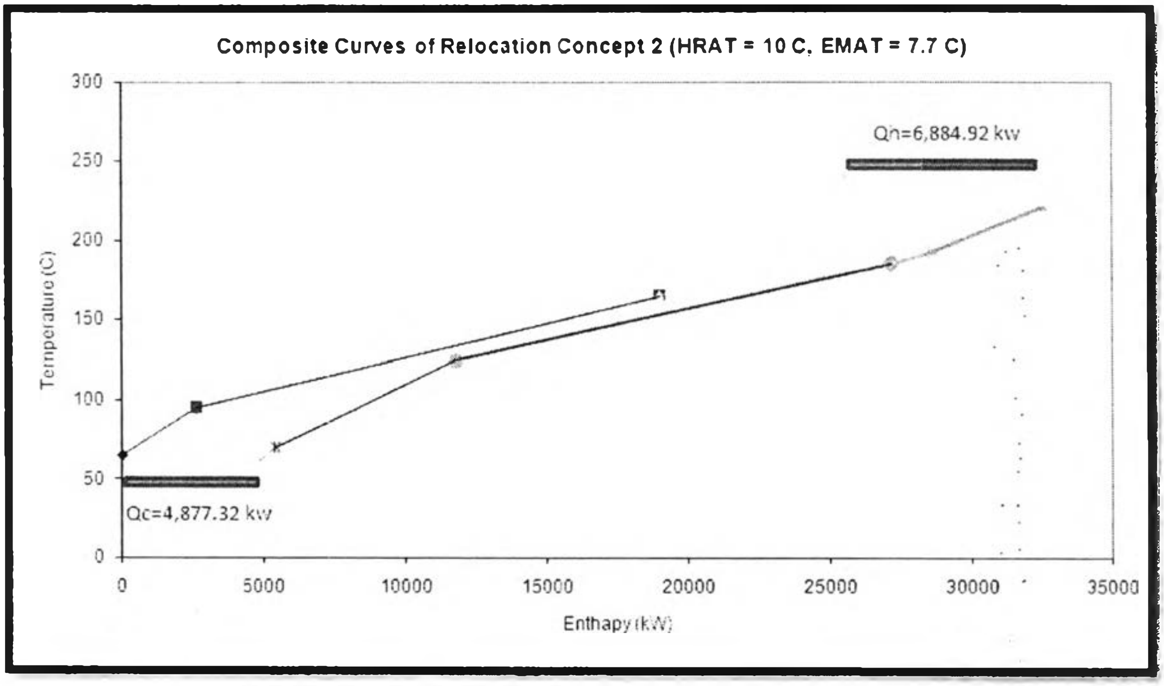

Figure 4.8 Composite curves of the optimal retrofit case with relocation concept 2.

The relocated and new exchangers of the retrofit case with relocation concept 2 are shown in Table 4.4.

Table 4.4 Result of retrofit design in concept 2 of example 1

UNIT	Heat Exchanger Area (m^2)	Heat Load (kW)	Area Cost $
E1*=E1+1635	1,767	1,432.507	311,382.74
E2*=E2+1321	1,909	1,159.994	260,870
E3*E3-277	449	3,980.093	-
E4*=E4-343	408	3,569.507	-
New1	766	7,316.274	172,552.84
New2	901	3,144.305	196,487.50
	$\sum = 6{,}200$		$\sum = 941{,}293.08$

**** This table doesn't include cost for moving, demolishing.*

4.1.3 Retrofit by PATHS COMBINATION of Example 1

Actually, heat exchanger network in base case of example 1 came from the research of Abdelbagi Osman, M.I. Abdul Mutalib, M. Shuhaimi and K.A. Amminudin [11]. They studied the retrofit design by paths combination method. And they had some conditions as shown below:

1. Investment is considered only for the required additional area.
2. No piping or other costs are considered.
3. Average size of heat exchanger shell is calculated from the existing HEN area and number of shells where one shell pass is assumed.
4. Existing average area per shell in HEN is the same as for the added area.
5. Material of construction is carbon steel for all exchanger.
6. Fixed energy price along the payback period.

They used paths combination to retrofit base case and this research brought the best four retrofit network structures (as shown in Figure 4.9 – 4.12) of them presented in Table 4.5. The retrofit of them has no relocation, splitting and new heat exchanger. They just have additional and removal area. We compared their result to retrofit design with relocation concept 1 and 2 of this research.

Table 4.5 Comparison of all methods

Options	Additional area requirement [m²]						Total Area (m²)	Additional Area Cost ($)	Utility Consuming				Utility cost ($/yr)	Profit ($)
	E1	E2	E3	E4	New1	New2			Q_H	Q_H saving (%)	Q_C	Q_C saving (%)		
1 (Figure 4.9)	163	0	597	0	0	0	2,947	180,877	9,893	12.26	7,885	14.91	1,344,860	302,823
2(Figure 4.10)	167	50	597	33	0	0	3,034	211,143	9,789	13.18	7,781	16.04	1,330,300	308,957
3(Figure 4.11)	123	-433	597	106	0	0	2,580	203,277	10,653	5.52	8,645	6.71	1,451,260	14,423
4(Figure 4.9)	163	0	597	38	0	0	2,985	194,440	9,850	12.64	7,842	15.38	1,338,840	304,310
concept1 (Figure 4.4)	276	-138	175	14	1,767	1,909	6,200	825,172.72	6,884.92	38.94	4,877.32	47.37	826,190.4	1,018,636
concept2 (Figure 4.7)	1,768	1,909	447	399	766	901	6,200	941,194.22	6,884.92	38.94	4,877.32	47.37	826,190.4	902,615

***hot utility = 120 $/KW/yr; cold utility = 20 $/KW/yr; Area cost was computed from eq.19 and eq.20*

From table 4.5, relocation of concept 1 and 2 can save utility consuming more than the others but new heat exchanger is added in concept 1 and 2. Relocation of concept1 and 2 can save 38.94 % of hot utility and 47.37 % of cold utility. Although they can save more utility consuming than the others, concept1 and concept 2 have the most additional area (almost twice). By the way, concept 2 is the better way than concept 1 because only one heat exchanger is moving as utility saving is the same.

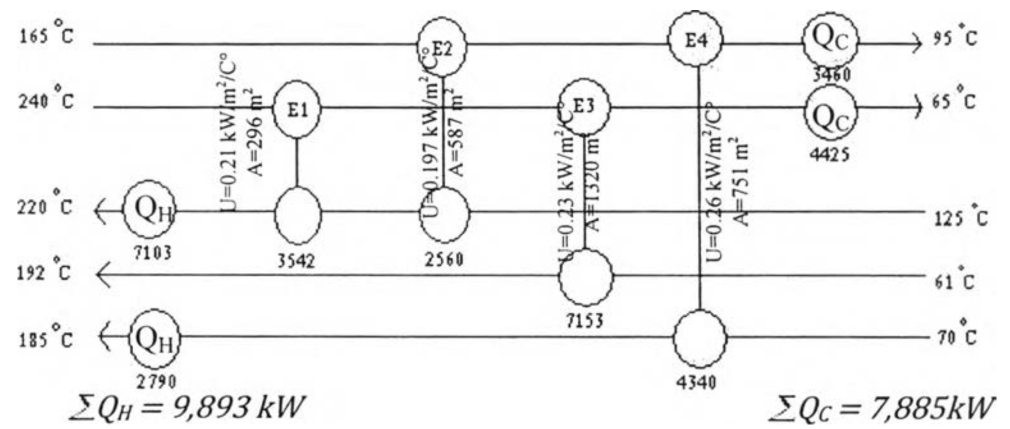

Figure 4.9 Retrofit 1 in grid diagram of example 1 in retrofit design by paths combination (EMAT=7.005).

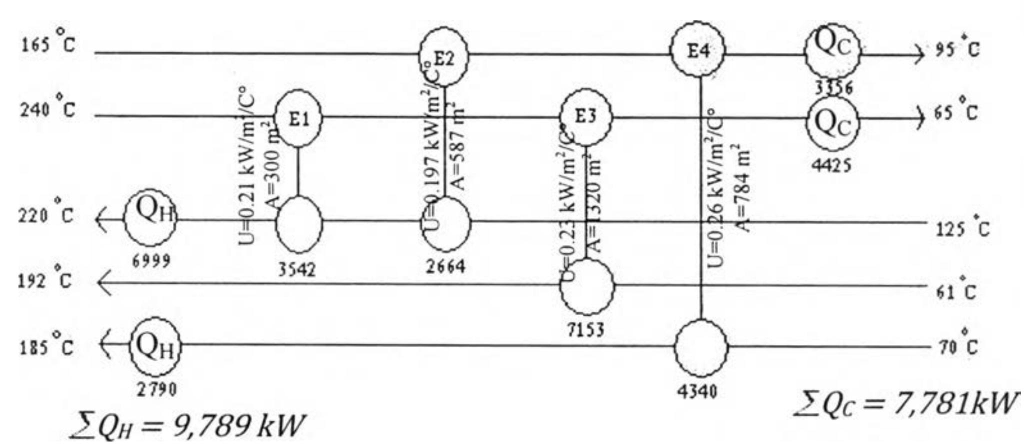

Figure 4.10 Retrofit 2 in grid diagram of example 1 in retrofit design by paths combination (EMAT=7.005).

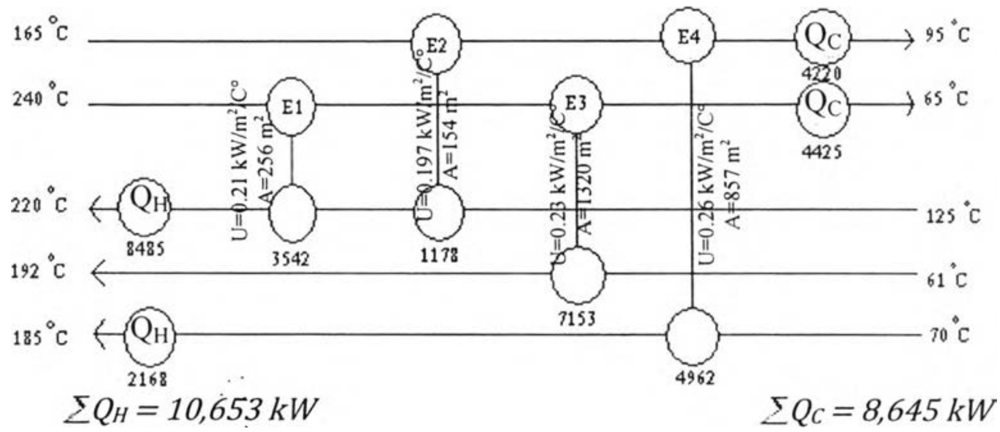

Figure 4.11 Retrofit 3 in grid diagram of example 1 in retrofit design by paths combination (EMAT=7.005).

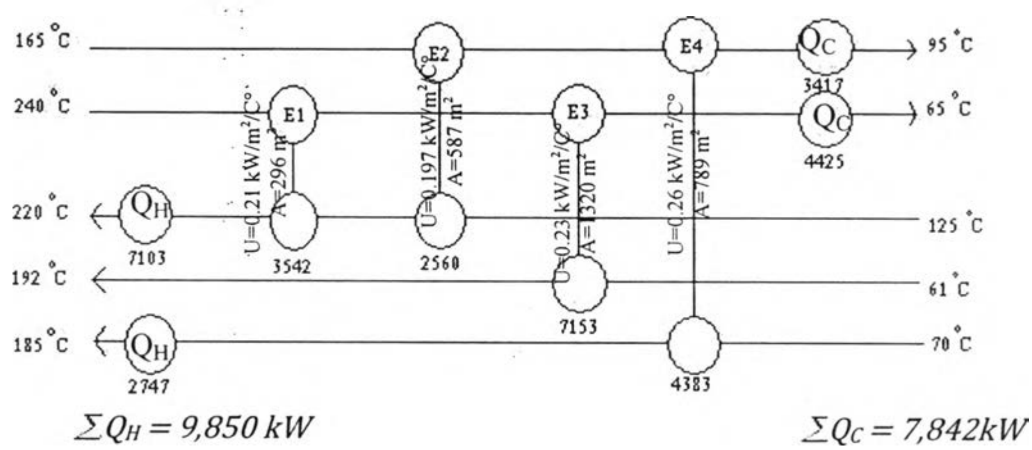

Figure 4.12 Retrofit 4 in grid diagram of example 1 in retrofit design by paths combination (EMAT=7.005).

4.2 Example 2

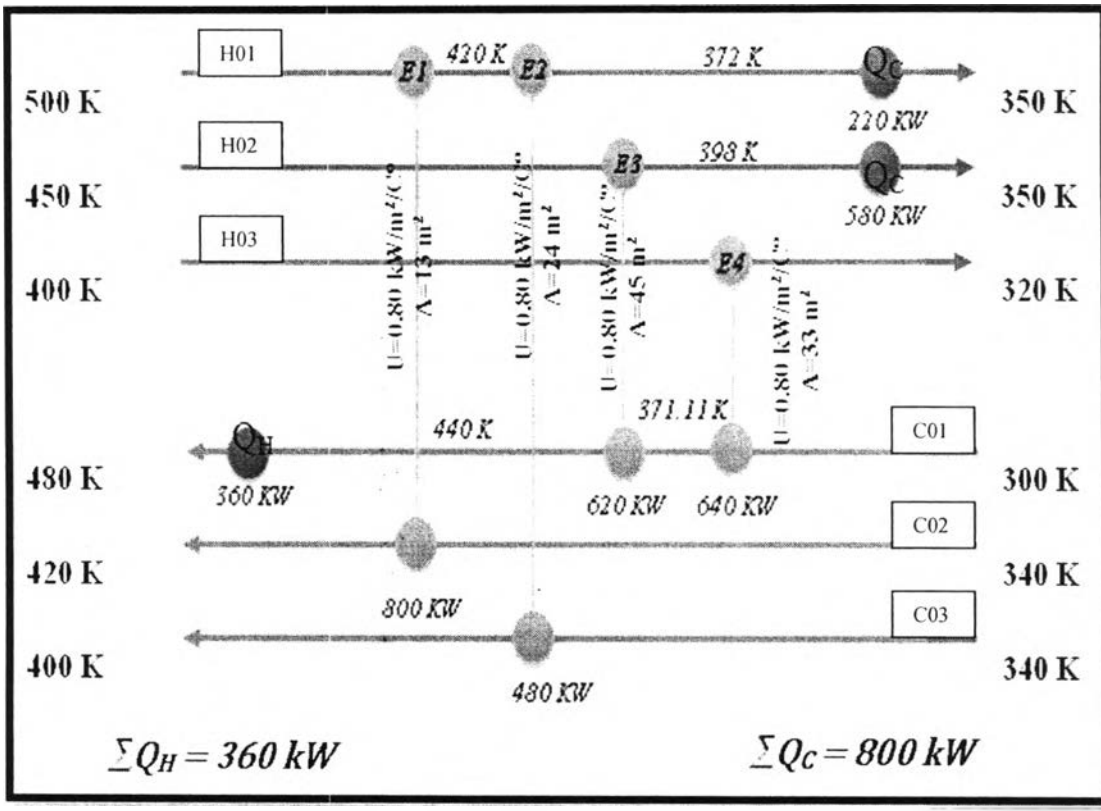

Figure 4.13 Grid diagram of base case in example 2*(EMAT = 10K)*.

A network consisting of three hot and three cold streams is investigated in this example draw from Ciric and Floudas(1990). Table 4.6 and 4.7 describe thermodynamic data of the example 2. Utility cost of the existing network is 44,800 \$/year. Ciric and Floudas (1990) and Ebrahim and Sirous (2009) **[12]** reduced it to 8,800 \$/year. The network in figure 4.16 and 4.19 are shown in concept 1 and concept 2, respectively and reduced to 8,800 \$/year as well. The comparison of result was shown in Table 4.10

Table 4.6 Thermodynamic data of example 2

Stream	T_{in}(K)	T_{out}(K)	FCp(kW/K)
H1	500	350	10
H2	450	350	12
H3	400	320	8
C1	300	480	9
C2	340	420	10
C3	340	400	8

Table 4.7 Information of base case of example 2

UNIT	Heat Exchanger Area (m^2)	Heat Load (kW)
E1	13	800
E2	24	480
E3	45	620
E4	33	640

(Information from above table was got from eq.20); (EMAT = 10 K)

Condition of solution

1. Nonsplitting
2. Cost of stream (\$/kW/year) = 80
3. Cost of cooling water (\$/kW/year) = 20
4. U = 0.80 kW/m^2 for all exchanger; LMTD is used for area calculation.
5. Cost of area for an existing exchanger(\$) = $300\Delta A$, A in m^2
6. Cost of area for a new exchanger (\$) = $1,200A^{0.6}$, A in m^2
7. Fixed cost of a new exchanger (\$) = 4,000
8. No cost for removal heat exchanger area
9. Plant life time = 5 year and % interest = 0

The composite curve of base case consumes hot and cold utilities of 800 and 360 kw, respectively, with HRAT = 20 K and EMAT= 10 K, as shown in the composite curves of Figure 4.14

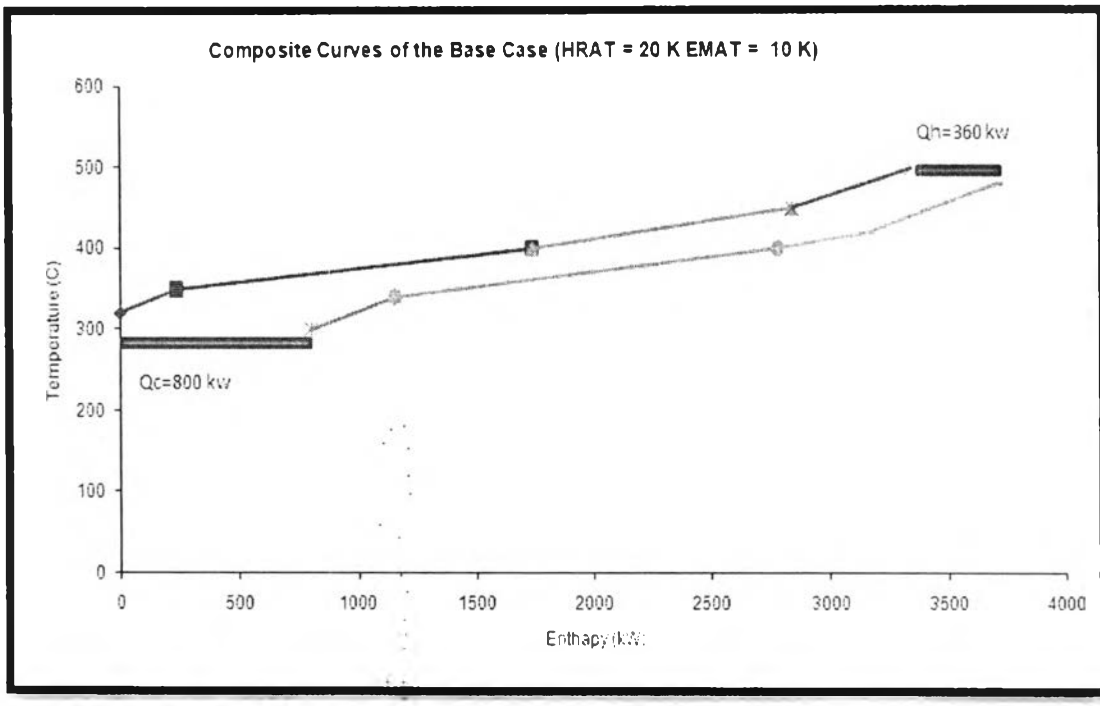

Figure 4.14 Composite curves of the base-case HEN in Example 2.

4.2.1 Retrofit with relocation concept1 of Example 2

Plot graph between profit($) and cold utility as shown in Figure 4.15 from eq.25 and maximum profit is chose to formulate retrofit case of relocation concept 1 in Figure 4.16.

The base-case HEN is retrofitted and relocated with concept 1 and 2 .The retrofitted HEN at different HRAT is generated by the retrofit model. Applying the program of the relocation concept 1, the profit of retrofitted HEN at different HRAT (or cold utility) is plotted as shown in Figure 4.15. And the optimal retrofitted HEN with relocation concept 1 is found as shown in figure 4.16, giving the maximum profit of $1,580,000 in 5 years.

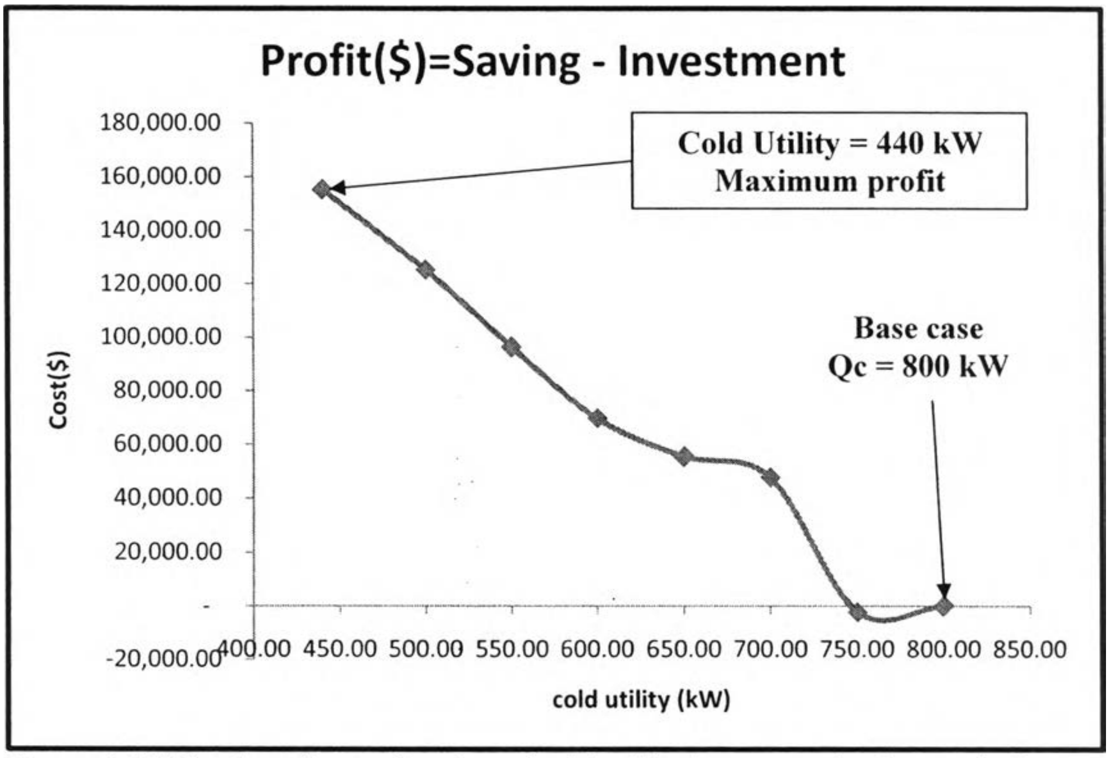

Figure 4.15 Total profit as a function of cold utility in concept 1 of example 2.

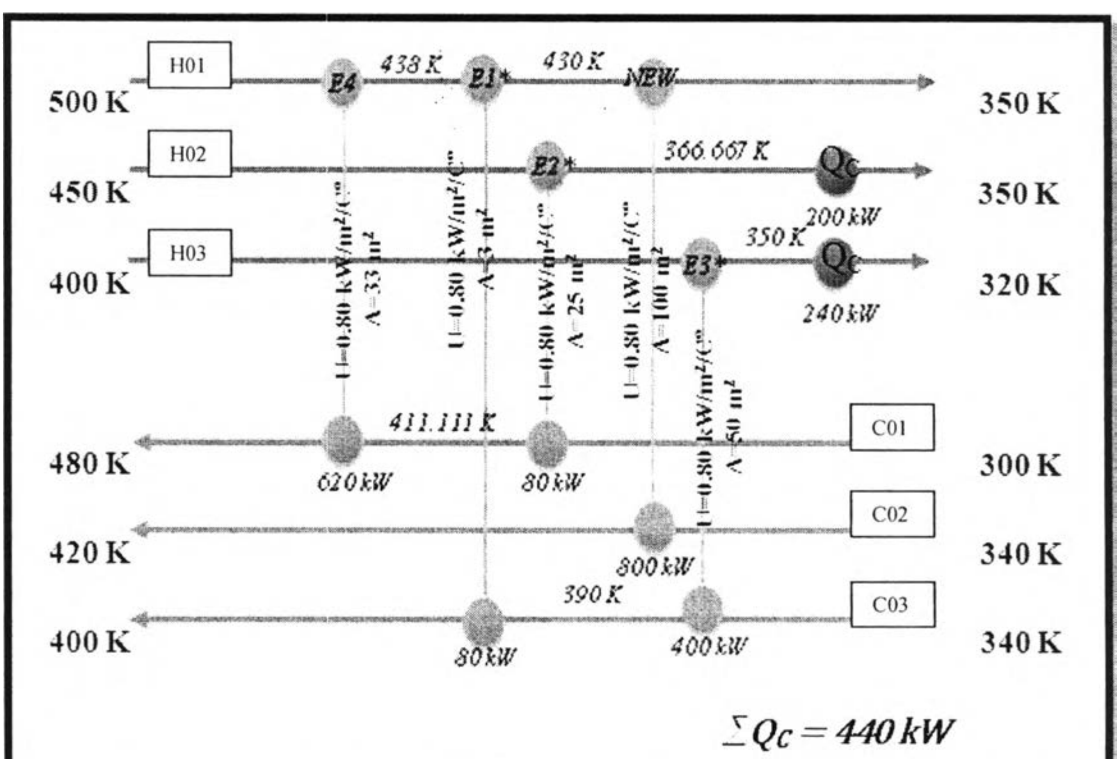

Figure 4.16 Grid diagram of example 2 in retrofit design in concept 1 *(EMAT = 12.732K)*.

The optimal retrofit case of relocation concept 1 consumes only cold utilities of 440 with HRAT = 12 K, as shown in the composite curves of Figure 4.17

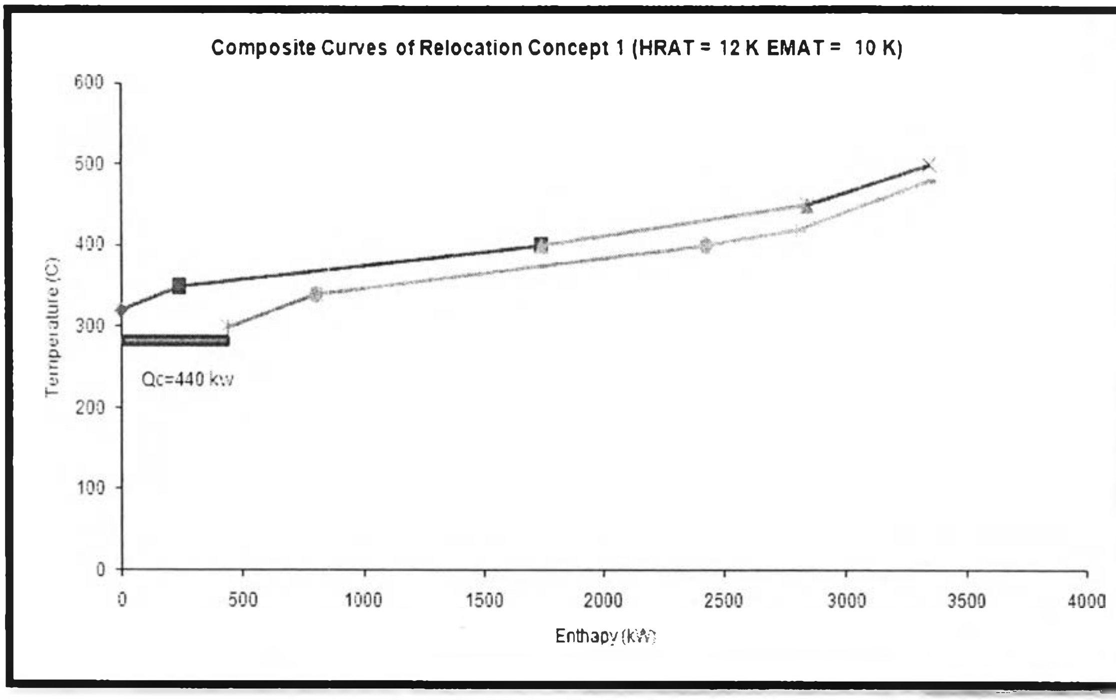

Figure 4.17 Composite curves of the optimal retrofit case with relocation concept 1.

Table 4.8 shows the result including heat exchanger area, heat load, additional area and cost of investment of retrofit model of example 2of concept1.

Table 4.8 Result of retrofit design in concept 1 of example 2 *(EMAT = 12.732)*

UNIT	Heat Exchanger Area (m^2)	Heat Load (kW)	Additional/Removal Area (m^2)	Cost of Additional and Removal Area ($)
E1*=E1-10	3	80	-10	-
E2*=E2+1	25	1,000	+1	300
E3*=E3+5	50	400	+5	1,500
E4	33	620	-	-
New	100	800	-	23,018.72
	$\sum = 211$			$\sum$ = 24818.72

**** This table doesn't include cost for moving, demolishing.*
Cold utility =440 kW and cold utility saving = 44.88%
Hot utility = 0 kW and hot utility saving = 100%

4.2.2 Retrofit with relocation concept 2 of Example 2

For the retrofit case with relocation concept 2, the retrofitted HEN at different HRAT are generated by the retrofit model. Applying the program of the relocation concept 2, the profit of retrofitted HEN at different HRAT (or hot utility) is plotted as shown in Figure 4.6. And the optimal retrofitted HEN with relocation concept 2 is found as shown in Figure 4.7, giving the maximum profit of $900,000 in 2.5 years.

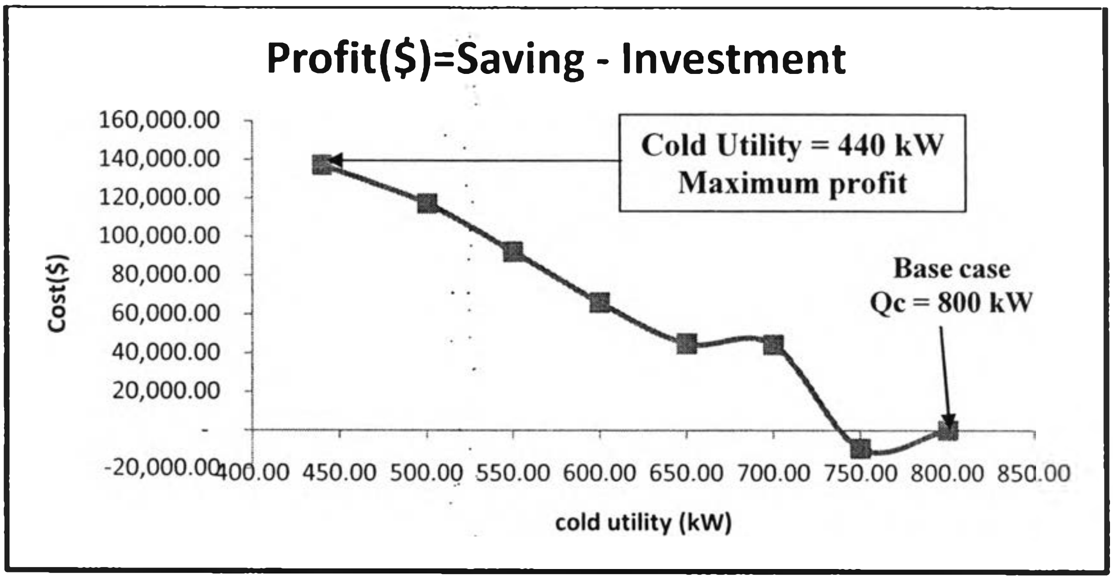

Figure 4.18 Total profit as a function of cold utility in concept 2 of example 2.

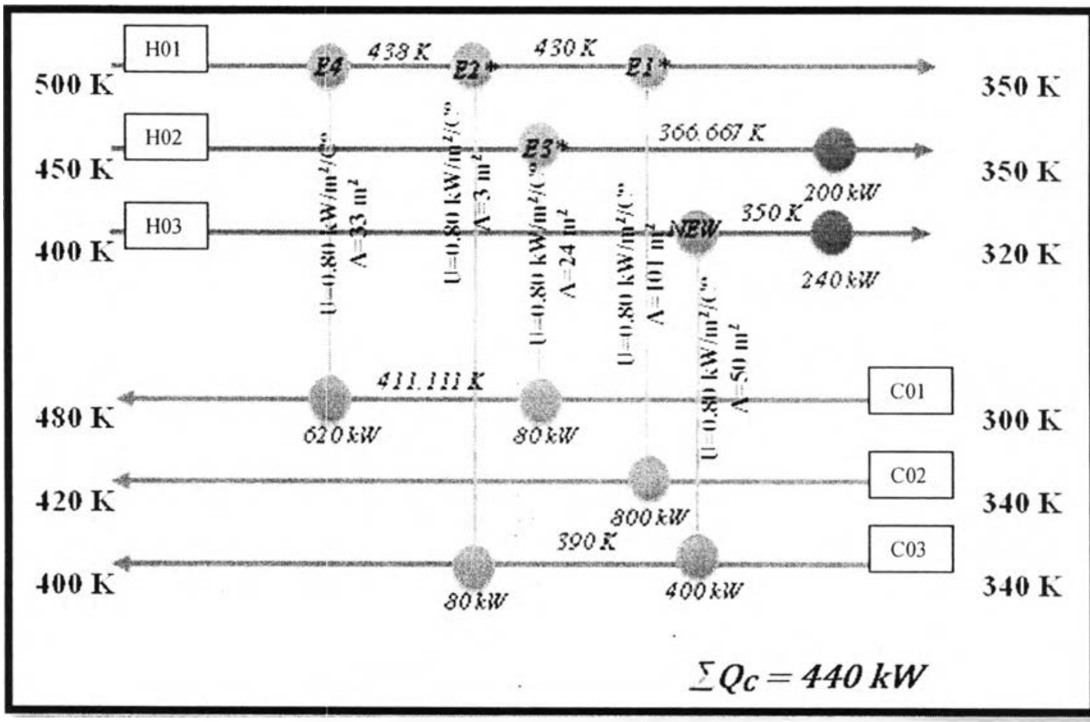

Figure 4.19 Grid diagram of example 2 in retrofit design in concept 2 *(EMAT = 12.732K).*

The optimal retrofit case consumes only cold utilities of 440 kw with HRAT = 12 K, as shown in the composite curves of Figure 4.20.

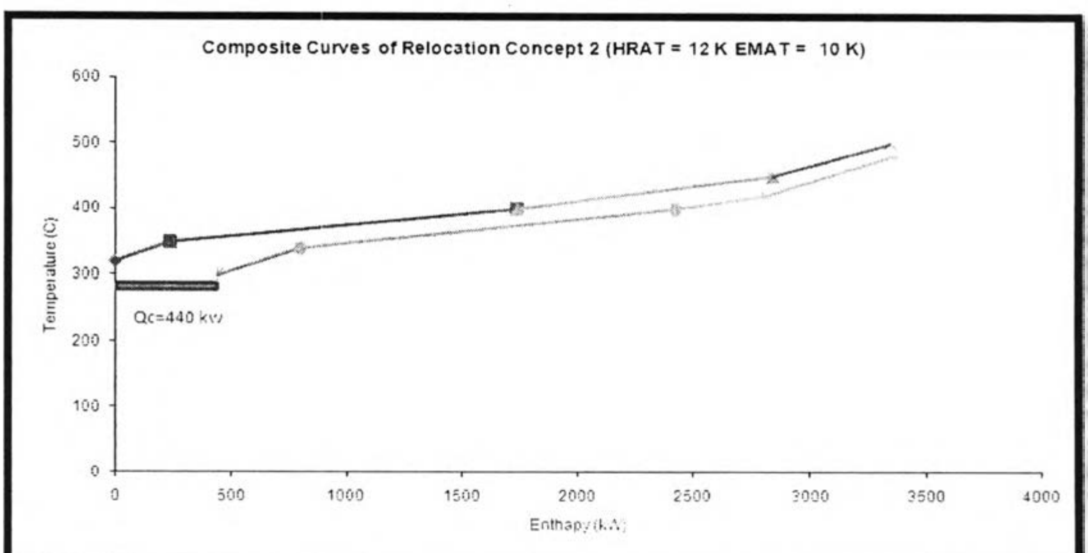

Figure 4.20 Composite curves of the optimal retrofit case with relocation concept 2.

Table 4.9 shows the result including heat exchanger area, heat load, additional area and cost of investment of retrofit model of example 2of concept2.

Table 4.9 Result of retrofit design in concept 2 of example 2

UNIT	Heat Exchanger Area (m^2)	Heat Load (kW)	Additional/Removal Area (m^2)	Cost of Additional and Removal Area ($)
E1*=E1+88	101	800	+88	26,400
E2*=E2-21	3	80	-21	-
E3*=E3-21	24	1,000	-21	-
E4 .	33	620	-	-
New	50	400	-	16,547.67
	Σ=211			Σ=42,947.67

*** *This table doesn't include cost for moving, demolishing.*

Two existing heat exchangers (E2 and E3) of base case are moved to new matching in retrofit design.

Cold utility =440 kW and cold utility saving = 45%

Hot utility = 0 kW and hot utility saving = 100%

Table 4.10 Comparison of all methods of example 2

Options	Additional area requirement [m^2]					Total Area (m^2)	Additional Area Cost ($)	Utility Consuming				Profit ($)
	E1	E2	E3	E4	NEW			Q_H	Q_H saving (%)	Q_C	Q_C saving (%)	
Case study (Fig 4.15)	-10	-	+18	+8	+7	138	11,235	0	100	440	45	167,274
concept1 (Fig 4.12)	-10	+1	+5	-	100	211	24,818.72	0	100	440	45	155,228
concept2 (Fig 4 14)	+88	-21	-21	-	100	211	42947.67	0	100	440	45	137,135

From table 4.10, retrofit of concept 1 and concept 2 can reduce utility cost to 8,800 $/year like method of Ebrahim and Sirous (2009) **[12]** although their investment is more. In this work, concept 1 is better than concept 2 because of less investment and more profit.

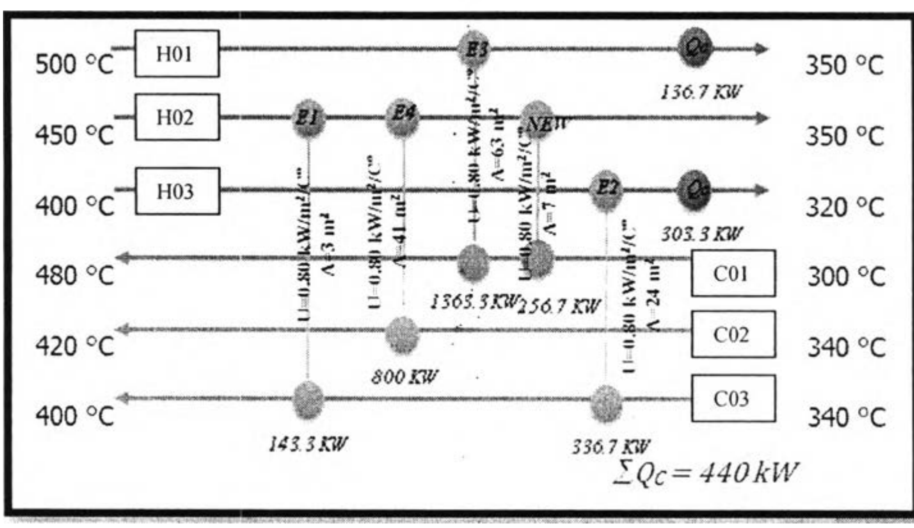

Figure 4.21 Grid diagram of example 2 of method of Ebrahim and Siro

4.3 Example 3

The path approach will be illustrated by the aromatics case, discussed by Tjoe (1986). The problem is summarized in Figure 4.22. The used data includes hot utility 27,100 kW; cold utility 23,495 kW. Thermodynamic data of example 3 is showed in table 4.11 and 4.12

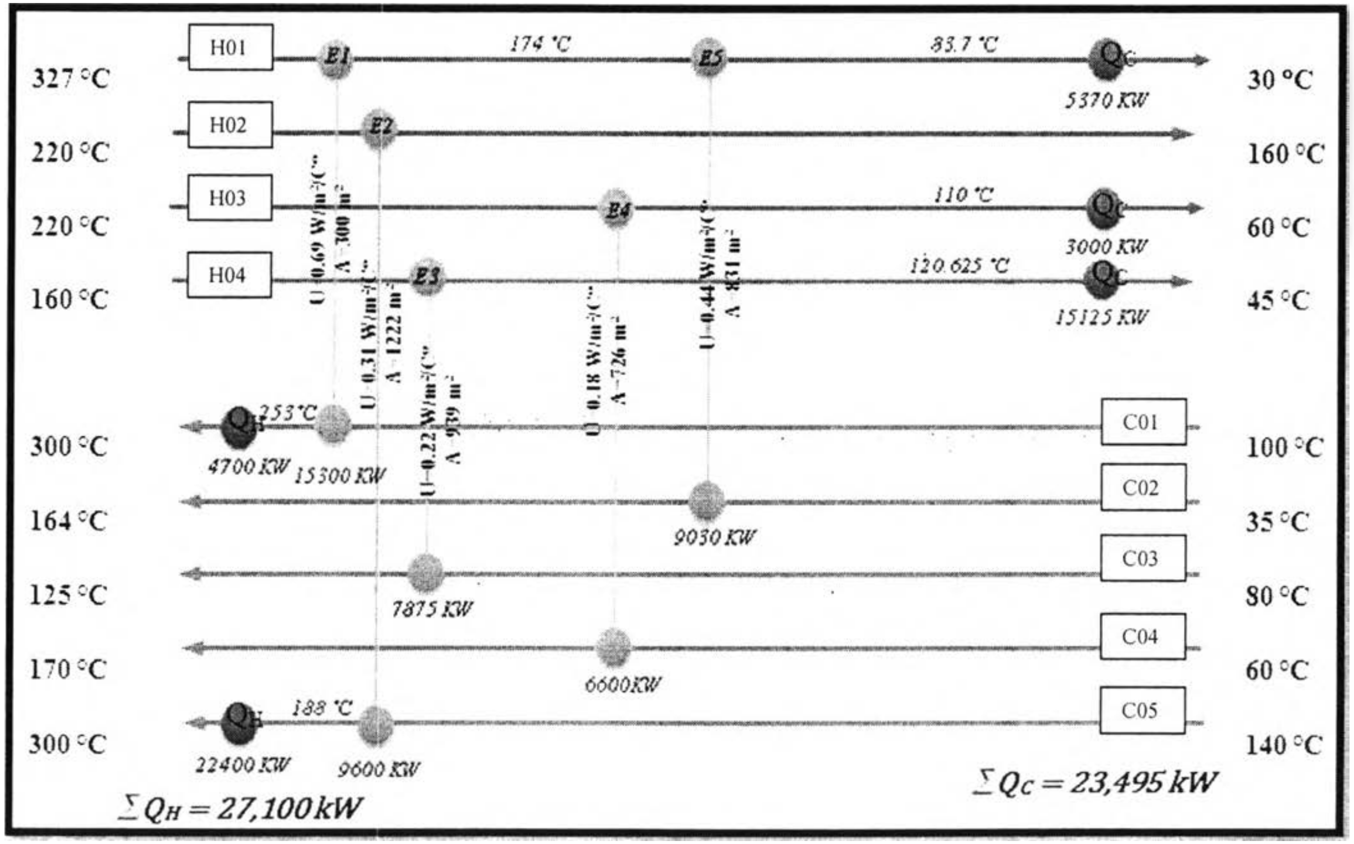

Figure 4.22 Grid diagram of example 3 in base-case *(EMAT = 10 °C)*

Table 4.11 Stream and cost data for the example 3 from Tjoe (1986)

Streams	T_{in}(°C)	T_{out}(°C)	F(kW/°C)	h(kW/m2°C)	Cost($/kW/year)
H1	327	30	100	0.80	
H2	220	160	160	0.50	
H3	220	60	60	2	
H4	160	45	200	0.40	
C1	100	300	100	5	
C2	35	164	70	1	
C3	80	125	175	0.50	
C4	60	170	60	0.20	
C5	140	300	200	0.80	
Stream					80
Water					20

Cost ($) = 30,000+750$A^{0.81}$ for all new exchangers, A in m^2; cost($) = 750$\Delta A^{0.81}$ for addition of area in existing exchangers, A in m^2; LMTD is used for area calculation. Nonsplitting will be focused. Plant life time = 3 years. % interedt=0.

Table 4.12 Information of base case of example 3

UNIT	Heat Exchanger Area (m^2)	Heat Load (KW)
E1	300	15,300
E2	1,222	9,600
E3	939	7,875
E4	726	6.600
E5	831	9,030

(Information from above table was got from eq.19 and 20); (EMAT = 10 °C)

The annual hot and cold utility consumption of the existing network is 27,100 kW and 23,495 kW, respectively as shown composite curves of Figure 4.23, corresponding to heat recovery approach temperature (HRAT) = 17 °C and exchanger minimum approach temperature (EMAT) = 10 °C.

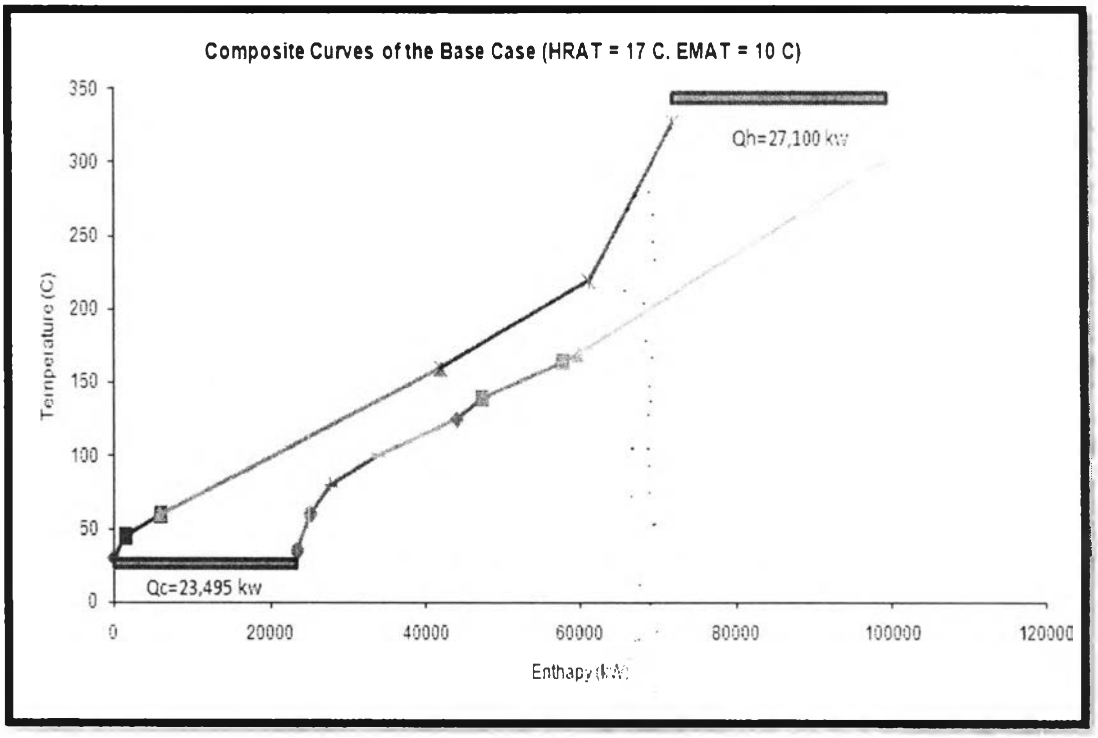

Figure 4.23 Composite curves of the base-case HEN in Example 3.

4.3.1 <u>Retrofit with relocation concept1 of Example 3</u>

Plot graph between profit($) and cold utility as shown in Figure 4.24 comes from eq.25 and maximum profit is chose to formulate retrofit case of relocation concept 1 in Figure 4.25. The base-case HEN is retrofitted and relocated with concept 1 and 2 .The retrofitted HEN at different HRAT is generated by the retrofit model. Applying the program of the relocation concept 1, the profit of retrofitted HEN at different HRAT (or cold utility) is plotted as shown in Figure 4.24. And the optimal retrofitted HEN with relocation concept 1 is found as shown in figure 4.25, giving the maximum profit of $1,000,000 in 3 years.

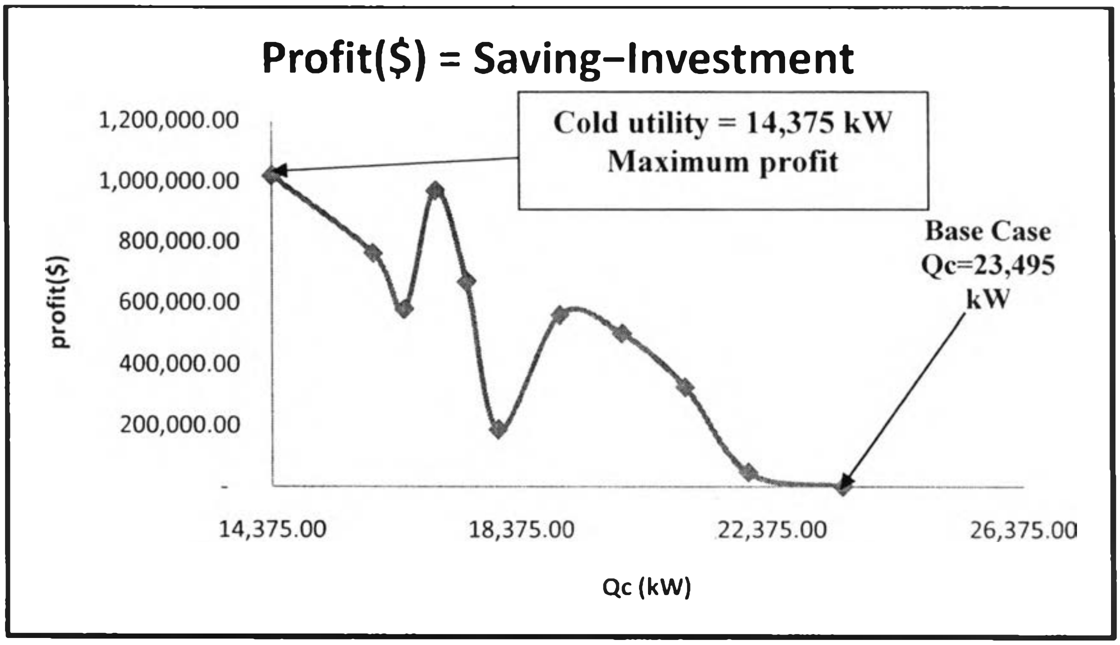

Figure 4.24 Total profit as a function of cold utility in concept 1 of example 3.

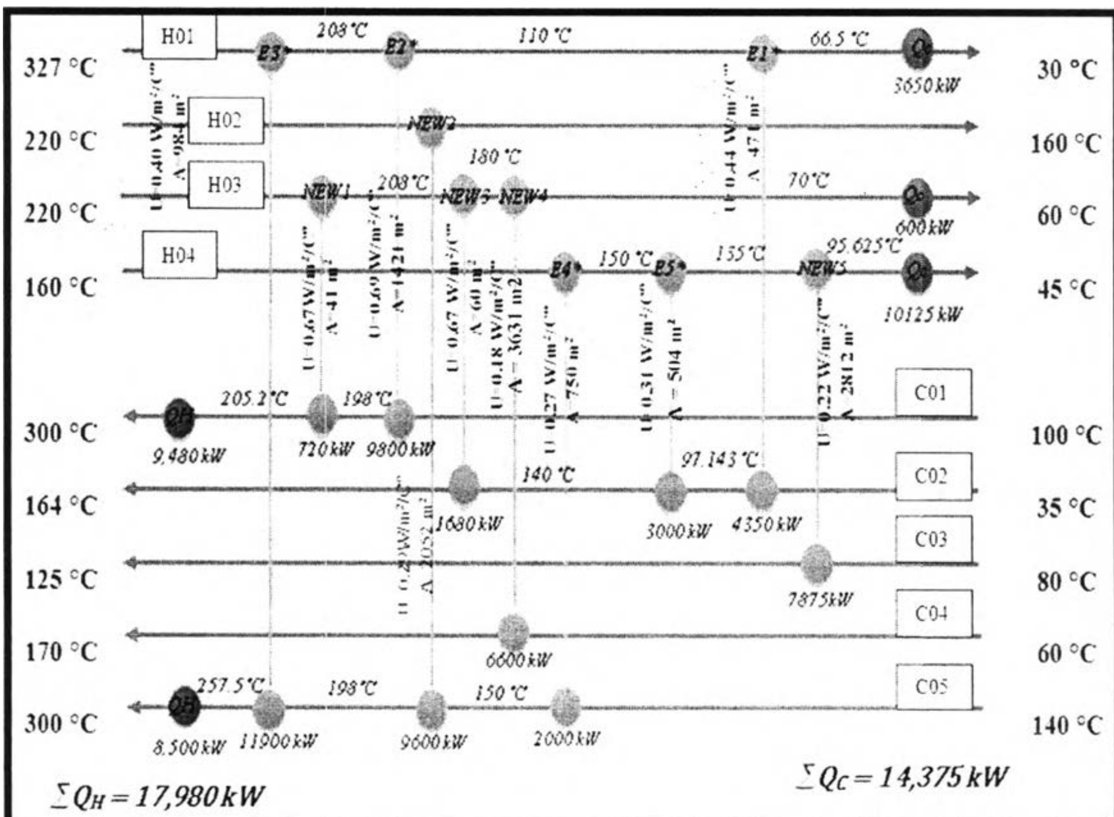

Figure 4.25 Modified network in retrofit design of example 3 in concept 1.

****(nonsplitting and EMAT = 10℃).*

The optimal retrofit case consumes hot and cold utilities of 17,980 and 14,375 kw, respectively, with HRAT = 10 °C, as shown in the composite curves of Figure 4.26

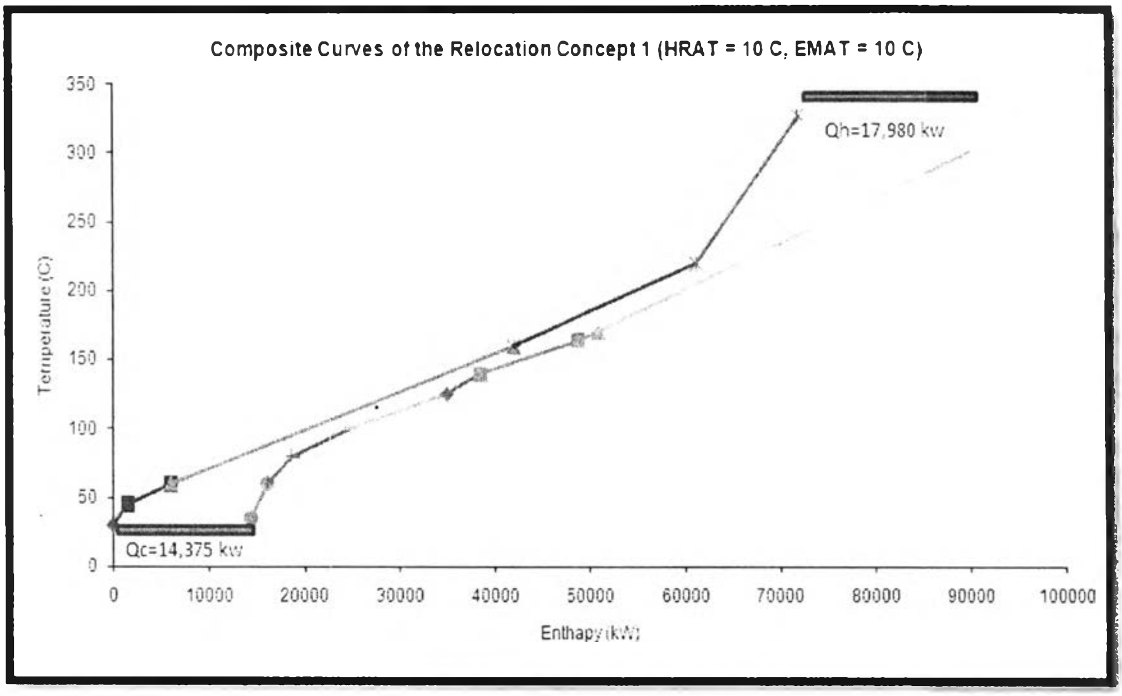

Figure 4.26 Composite curves of the optimal retrofit case with relocation concept 1.

Table 4.13 shows the result including heat exchanger area, heat load, additional area and cost of investment of retrofit model of example 3of concept1.

Table 4.13 Result in retrofit design in concept 1 of example 3

UNIT	Heat Exchanger Area (m^2)	Heat Load (kW)	Additional Area (m^2)	Cost of Additional and Area ($)
E1*=E1+171	471	4,350	171	48,282.32
E2*=E2+199	1,421	9,800	199	54,592.41
E3*=E3+45	984	11,900	45	16,374.32
E4*=E4+24	750	2,000	24	9,840.84
E5*=E5-334	504	3,000	-	-
New1	41	720	-	45,185.05
New2	2,052	9,600	-	391,347.39
New3	60	1,680	-	50,671.11
New4	3,631	6,600	-	118,835.31
New5	2,812	7,875	-	496,405.51
	Σ=12,726			Σ=1,231,534.26

4.3.2 Retrofit with relocation concept 2 of Example 3

For the retrofit case with relocation concept 2, the retrofitted HEN at different HRAT is generated by the retrofit model. Applying the program of the relocation concept 2, the profit of retrofitted HEN at different HRAT (or cold utility) is plotted as shown in Figure 4.27. And the optimal retrofitted HEN with relocation concept 2 is found as shown in Figure 4.28, giving the maximum profit of $900,000 in 3 years.

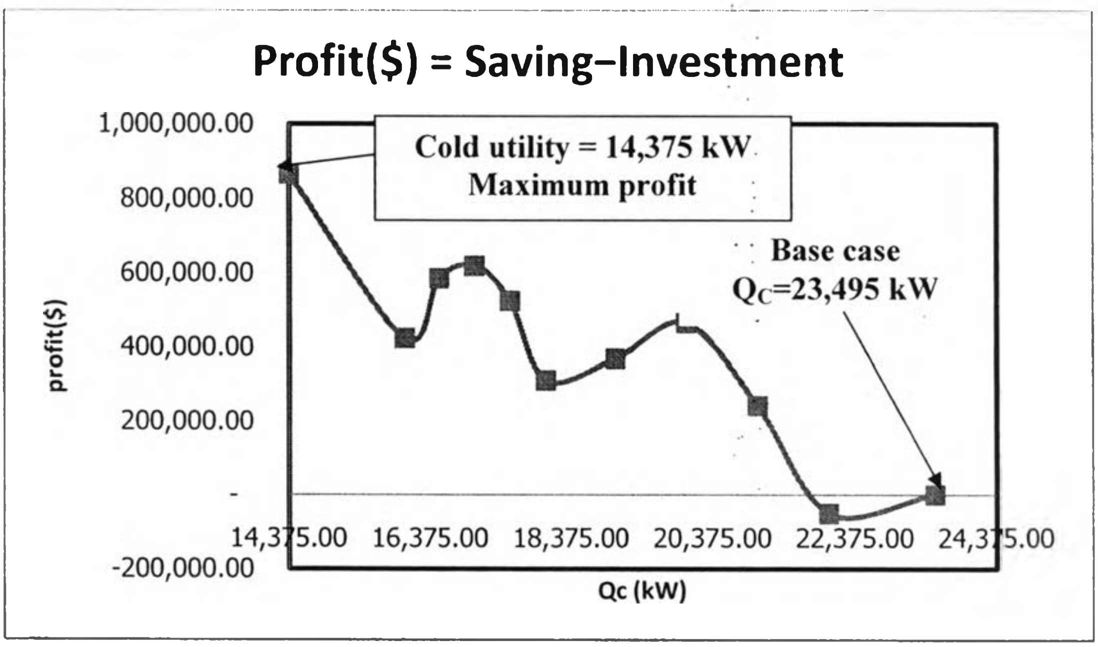

Figure 4.27 Total profit as a function of cold utility in concept 2 of example 3.

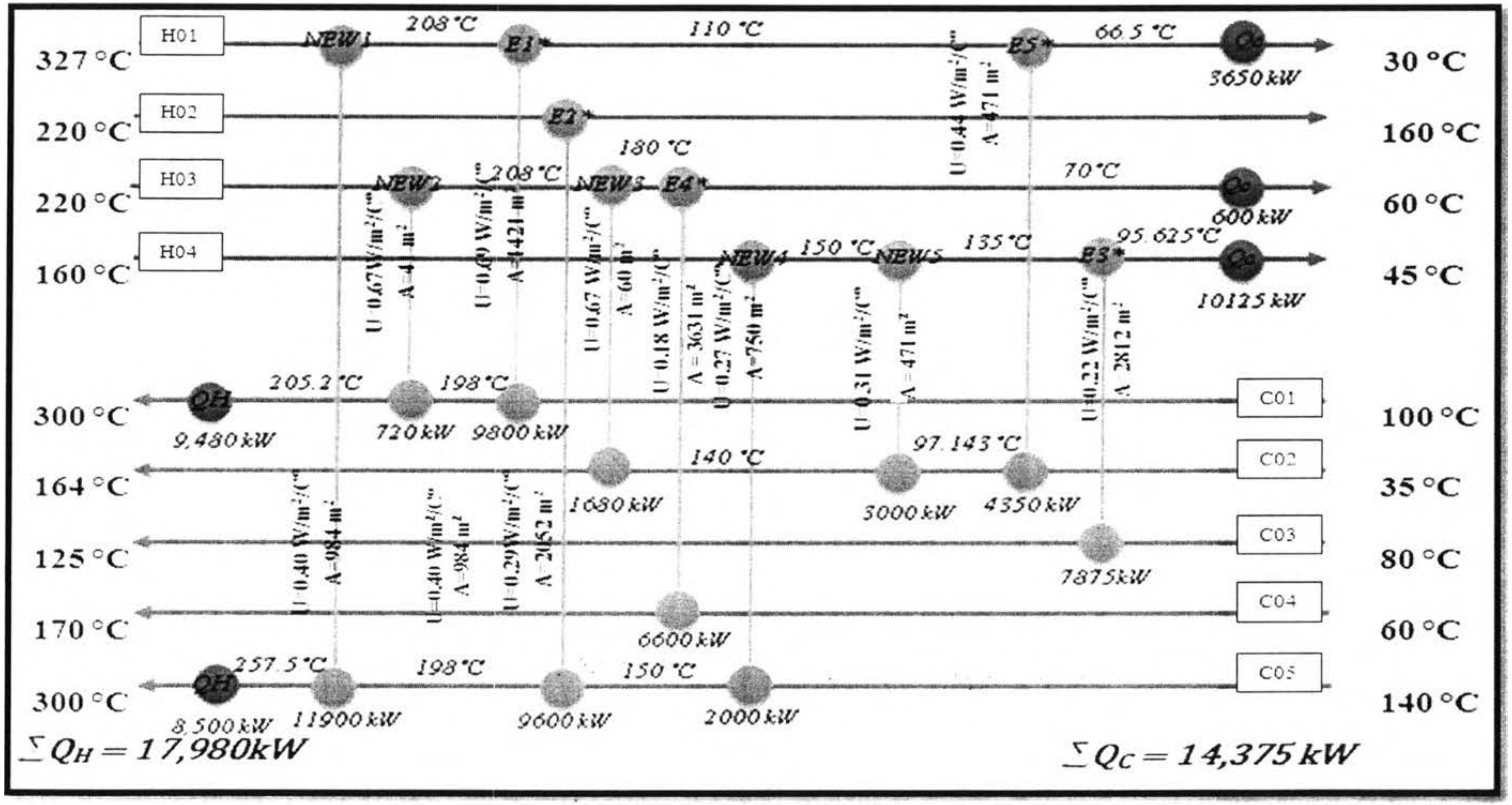

Figure 4.28 Modified network in retrofit design of example 3 in concept 2.

****(nonsplitting and EMAT = 10 °C)*

The optimal retrofit case consumes hot and cold utilities of 17,980 and 14,375 kw, respectively, with HRAT = 10 C°, as shown in the composite curves of Figure 4.29

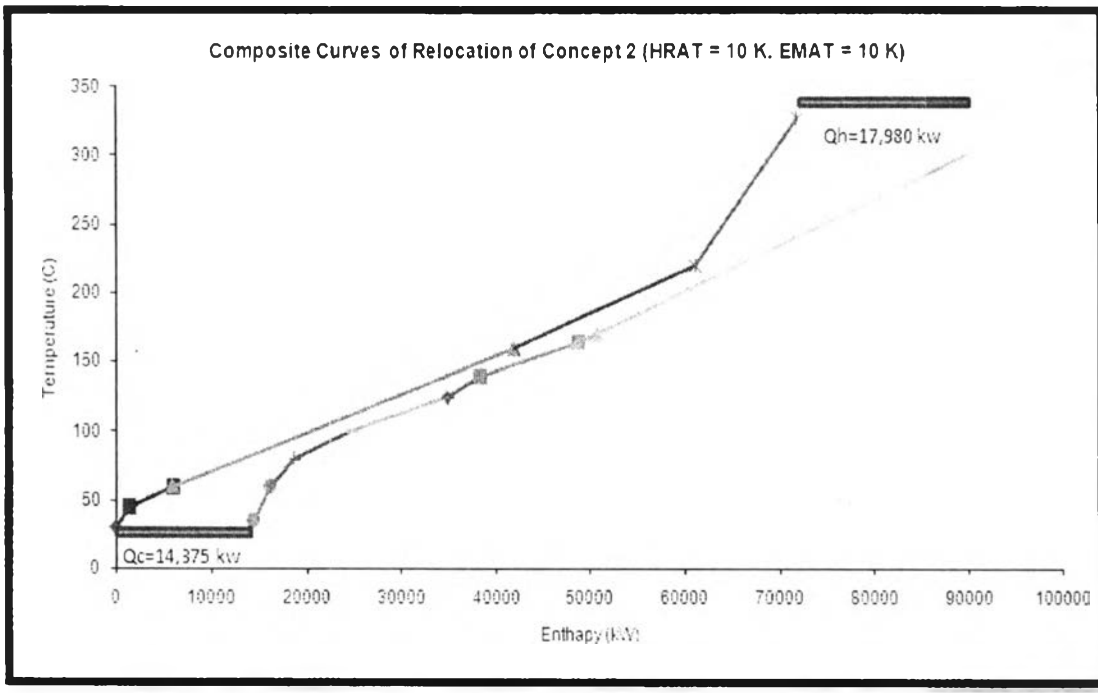

Figure 4.29 Composite curves of the optimal retrofit case with relocation concept 2.

Table 4.14 shows the result including heat exchanger area, heat load, additional area and cost of investment of retrofit model of example 3of concept 2.

Table 4.14 Result in retrofit design in concept 2 of example 3

UNIT	Heat Ex-changer Area (m^2)	Heat Load (kW)	Additional Area (m^2)	Cost of Addi-tional Area ($)
E1*=E1+1121	1,421	9,800	1,121	221,432.73
E2*=E2+829	2,051	9,600	829	173,416.51
E3*=E3+1873	2,812	7,875	1,873	335,596.07
E4*=E4+2905	3,631	6,600	2,905	478,861.18
E5*=E5-366	471	4,350	-	-
New1	984	11,900	-	229,244.94
New2	41	720	-	45,185.05
New3	60	1,680	-	50,671.11
New4	750	2,000	-	189,904.57
New5	504	3,000	-	145,885.74
	Σ=12,726			Σ=1,870,197.9

From base-case, retrofit model of JOS L.B. VAN REISEN et al is shown in figure 4.30 and can reduce hot and cold utility to 23,475(13.38%) and 19,870 kW(15.43%), respectively. This model doesn't change any existing heat exchanger but three new heat exchangers are added. As well as relocation of concept 1 and 2 (is shown in figure 4.25 and 4.28, respectively) can reduce more hot and cold utility (data is shown in table 4.15) and give more profit although they have more investment.

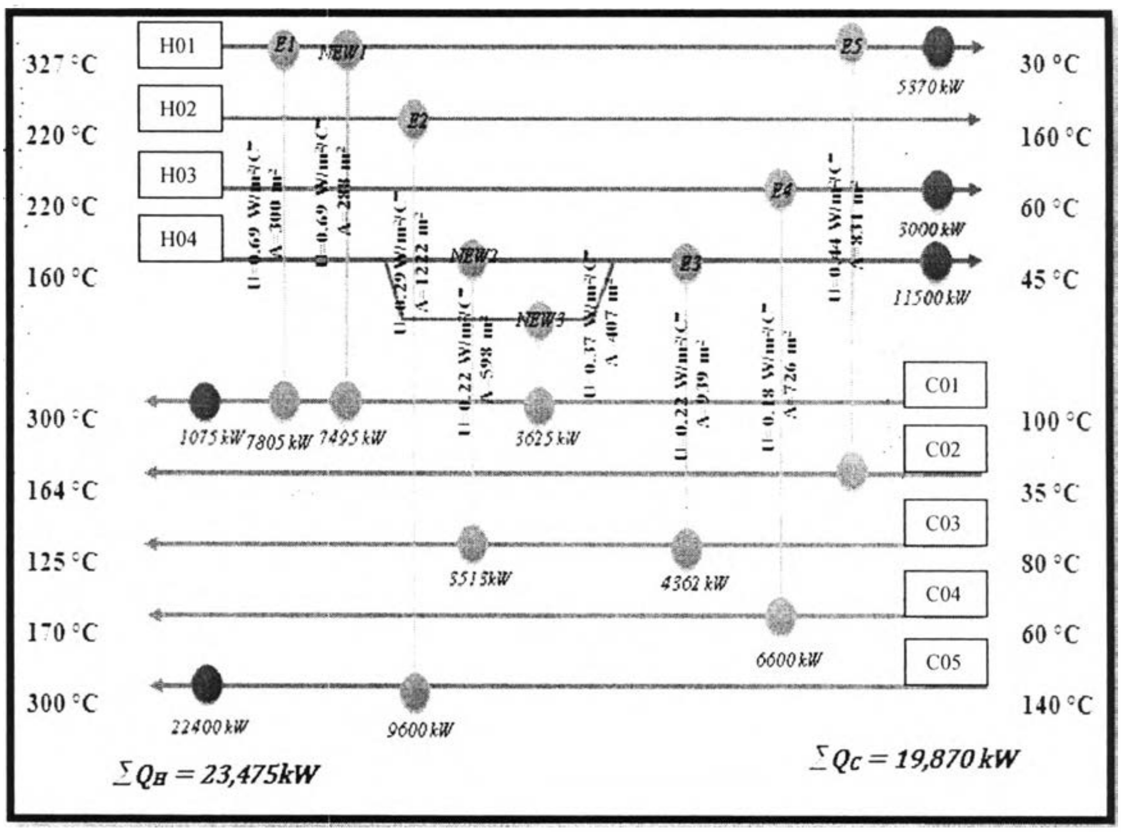

Figure 4.30 Modified network in retrofit design of example 3 of JOS L.B. VAN REISEN et al.

Table 4.15 Comparison of all methods of example 3

Options	Additional area requirement [m²]										Total Area (m²)	Additional Area Cost ($)	Utility Consuming				Utility cost ($/yr)	Profit ($)
	E1	E2	E3	E4	E5	New1	New2	New3	New4	New5			Q_H	Q_H saving (%)	Q_C	Q_C saving (%)		
Case study (Fig.4.30)	-	-	-	-	-	288	598	407	-	-	5,311	394,214.24	23,475	13.38	19,870	15.43	2,275,400	693,285.76
concept1 (Fig 4.25)	171	199	45	24	-334	41	2,052	60		3631 / 3,812		12,726 / 1,7[illegible]6,448.99	17,980	33.65	14,375	38.82	1,725,900	1,019,551.01
concept2 (Fig 4.28)	1,121	829	1,873	2,905	-366	984	41	60	750	504		12,726 / 1,3[illegible]6,398.52	17,980	33.65	14,375	38.82	1,725,900	865,601.48

4.4 Example 4

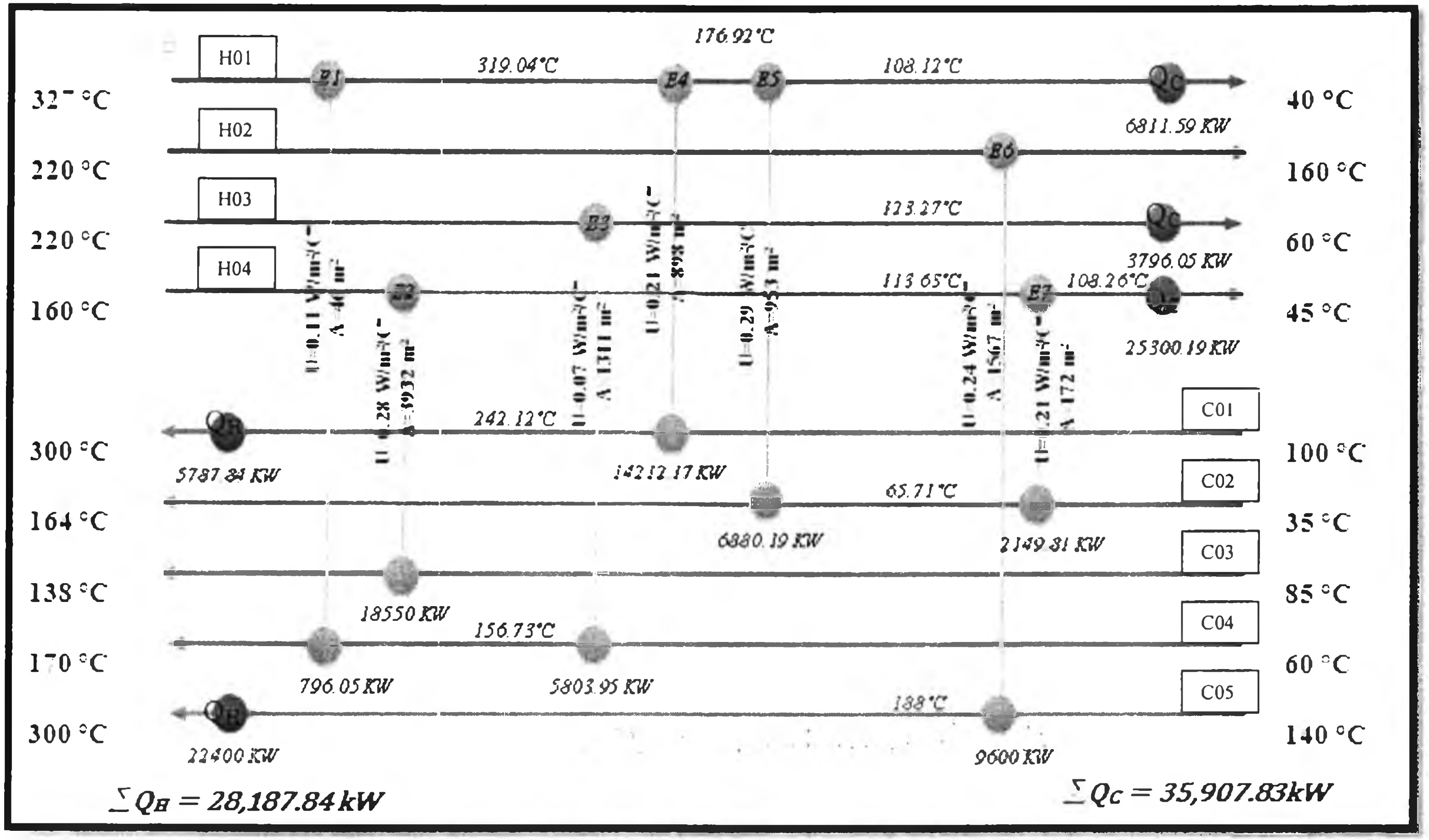

Figure 4.31 Grid diagram of example 4 in base-case *(EMAT = 12.92 ℃)*.

The example 4 (Figure 4.31) is a medium size problem with nine process streams and two utilities. The data is shown in Table 4.16 and 4.17. This network consists of four hot streams and five cold streams and seven heat exchangers. The annual hot and cold utility consumption of the existing network is 28,187.84 kW and 35,907.83 kW, respectively as shown composite curves of Figure 4.32, corresponding to heat recovery approach temperature (HRAT) = 16 °C and exchanger minimum approach temperature (EMAT) = 10 °C.

Table 4.16 Process stream and cost data of example 4

Stream	FCP(kW/°C)	T_{in}(°C)	T_{out}(°C)	h(kW/m^2°C)
H1	100	327	40	0.50
H2	160	220	160	0.40
H3	60	220	60	0.14
H4	400	160	45	0.30
C1	100	100	300	0.35
C2	70	35	164	0.70
C3	350	85	138	0.50
C4	60	60	170	0.14
C5	200	140	300	0.60

EMAT = 12.92 °C

Cost model of new heat exchangers ($/year): a + (b×Area^c); a = 2000; b = 70, c = 1.0 (Area unit of m^2).

Cost model of additional heat exchanger ($/year):b×Area^c; b = 70, c = 1.0 (Area unit of m^2).

Cost of utilities: HU(stream) = 60 $/kW/year; CU(cooling water) = 6.0 $/kW/year.

Economic data: rate of interest = 0%; Project life time = 5 years.

Table 4.17 Information of base case of example 4

UNIT	Heat Exchanger Area (m^2)	Heat Load (kW)
E1	46	796.05
E2	3,932	18,550
E3	1,311	5,803.95
E4	898	14.212.17
E5	953	6.880.19
E6	1,567	9.600
E7	172	2,149.81

(Information from above table was got from eq.20); (EMAT = 12.92K)

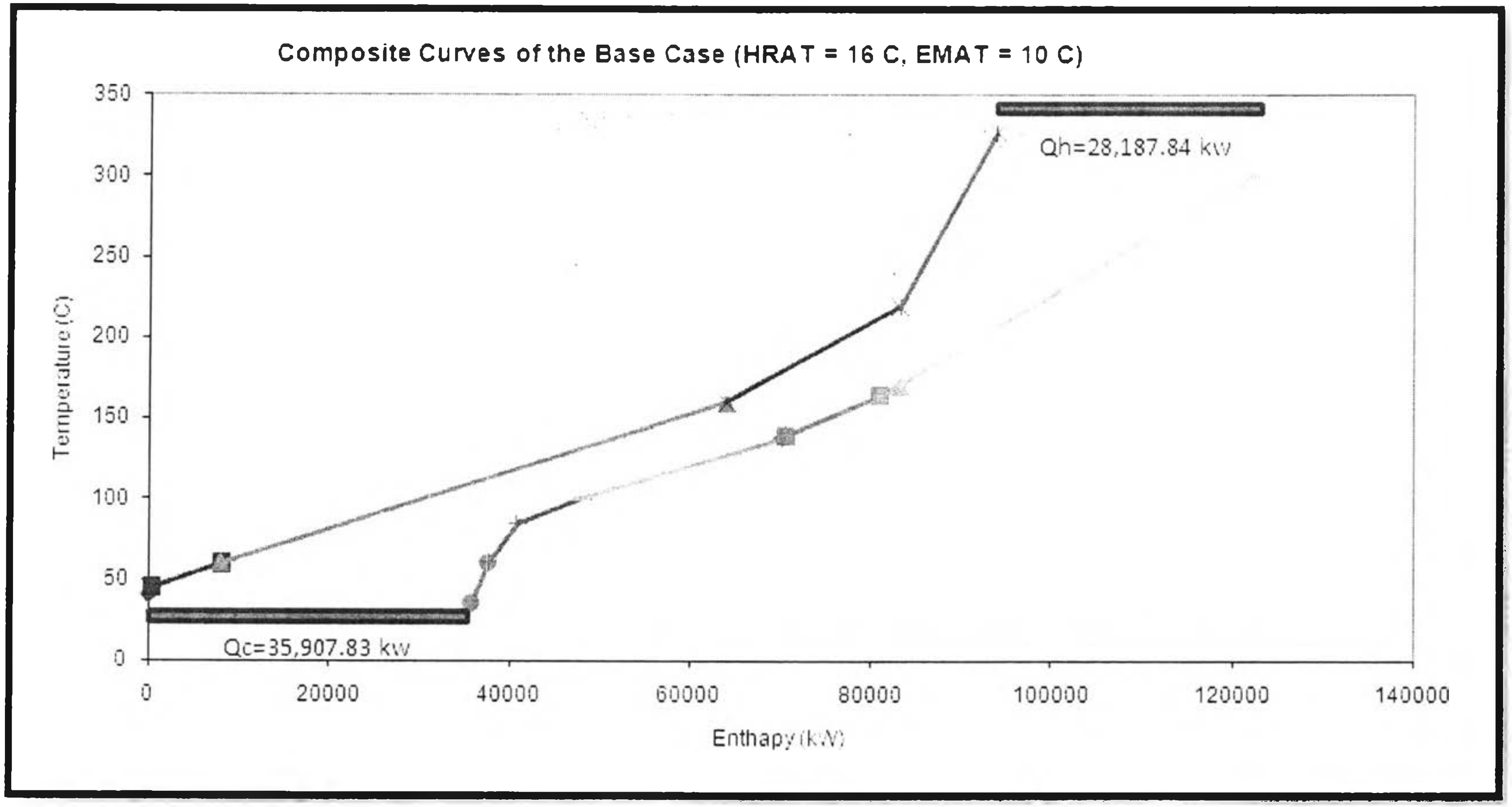

Figure 4.32 Composite curves of the base-case HEN in Example 4.

4.4.1 Retrofit with relocation concept 1 of Example 4

Plot graph between profit ($) and hot or cold utility as shown in Figure 4.33. The profit of the retrofit case is calculated by eq.25

The base-case HEN is retrofitted by using retrofit model of GAMS with MILP (Mixed Integer Linear Programming) and the relocation program with concept 1 and 2 using Visual C++. The retrofitted HEN at different HRAT is generated by the retrofit model. Applying the program of the relocation concept 1, the profit of retrofitted HEN at different HRAT (or cold utility) is plotted as shown in Figure 4.33. And the optimal retrofitted HEN with relocation concept 1 is found as shown in figure 4.34, giving the maximum profit of $1,900,000 in 5 years.

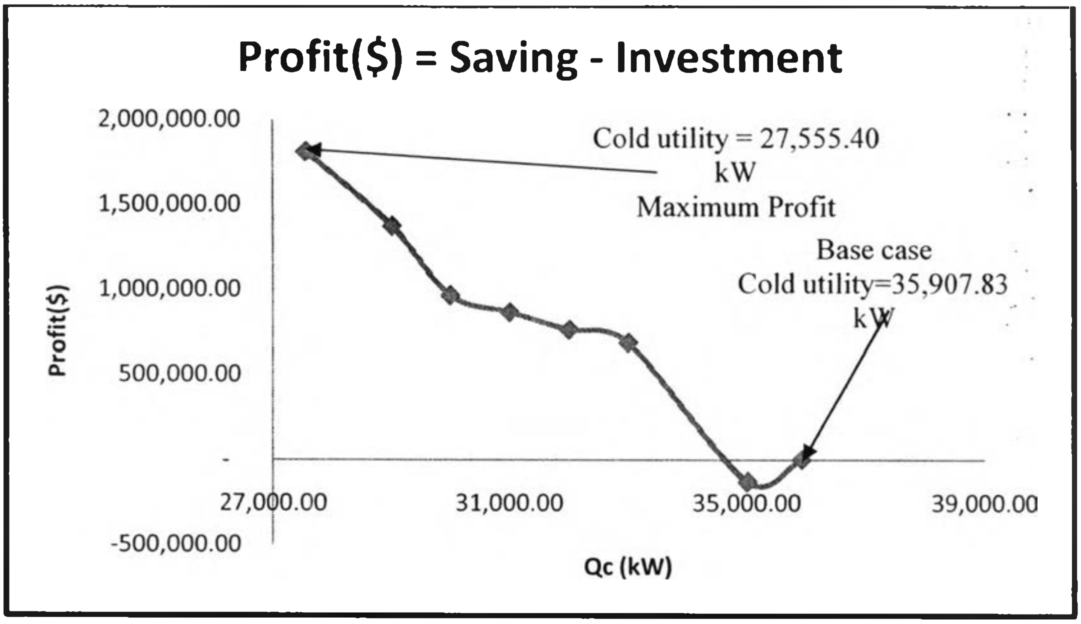

Figure 4.33 Total profit as a function of cold utility in concept 1 of example 4.

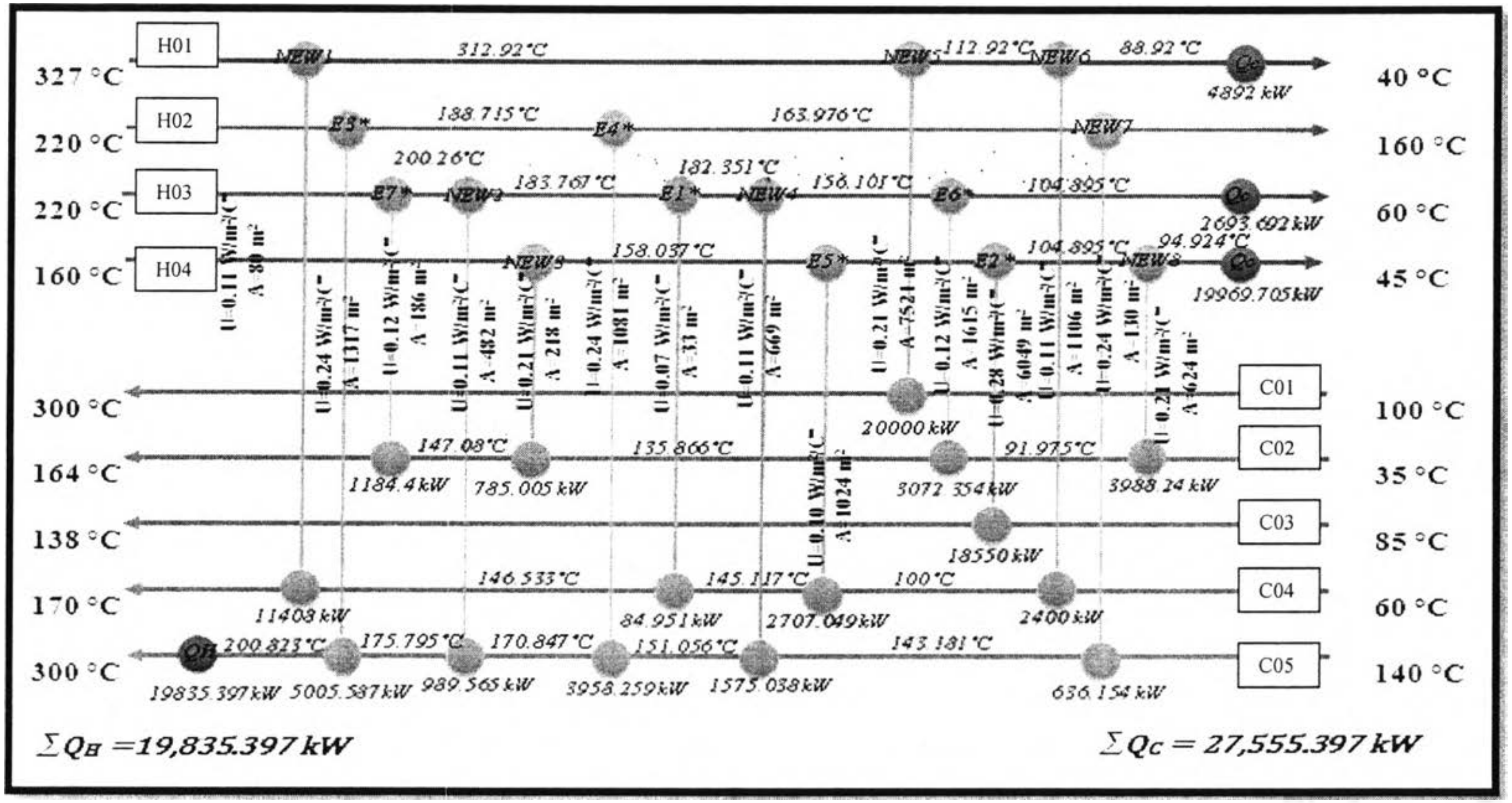

Figure 4.34 Modified network in retrofit design of example 4 in concept 1.

****(nonsplitting and EMAT = 12.92K)*

The optimal retrofit case consumes hot and cold utilities of 19,835.37 and 27,555.40 kw, respectively. with HRAT = 8 °C, as shown in the composite curves of Figure 4.35.

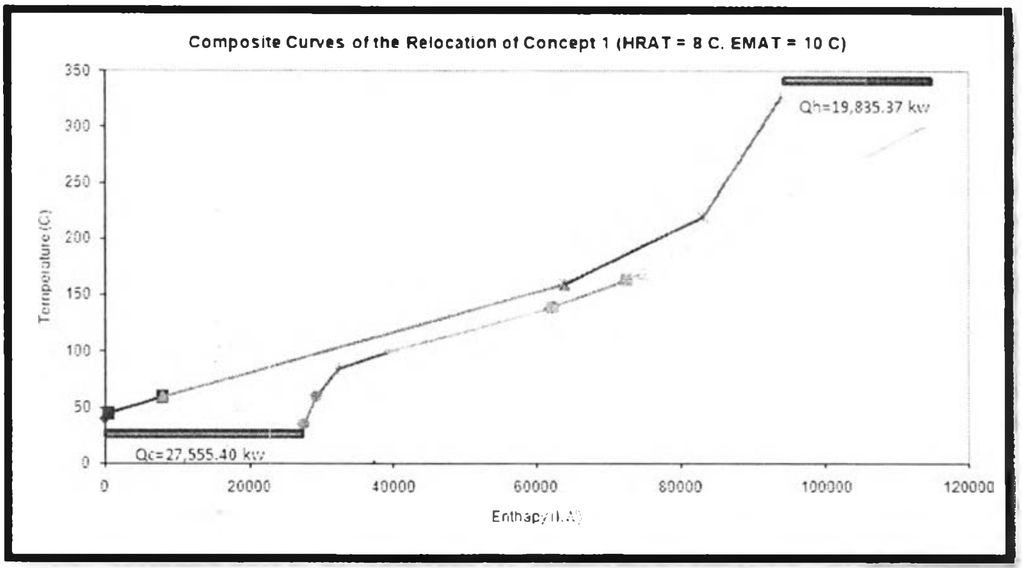

Figure 4.35 Composite curves of the optimal retrofit case with relocation concept 1 of example 4.

Table 4.18 shows the result including heat exchanger area, heatload, additional area and cost of investment of retrofit model of example 4 of concept 1.

Table 4.18 Result in retrofit design in concept 1 of example 4

UNIT	Heat Exchanger Area (m^2)	Heat Load (kW)	Additional Area (m^2)	Cost of Additional and Removal Area ($)
E1*=E1-13	33	84.951	-	-
E2*=E2-2117	6049	18.550	2117	148,190
E3*=E3-6	1317	5,005.587	6	420
E4*=E4-183	1081	3,958.259	183	12,810
E5*=E5-71	1024	2,707.049	71	4,970
E6*=E6-48	1615	3,072.354	48	3,360
E7*=E7-14	186	1,184.41	14	980
NEW1	80	1.408	-	7,600
NEW2	482	989.565	-	35,740
NEW3	218	785.005	-	17,260
NEW4	669	1,575.038	-	48,830
NEW5	7521	20.000	-	528.470
NEW6	1106	2,400	-	79,420
NEW7	130	636.154		11,100
NEW8	624	3,988.24	-	45.680
	∑=22.135			∑=944.830

4.4.2 Retrofit with relocation concept 2 of Example 4

For the retrofit case with relocation concept 2, the retrofitted HEN at different HRAT is generated by the retrofit model. Applying the program of the relocation concept 2, the profit of retrofitted HEN at different HRAT (or cold utility) is plotted as shown in Figure 4.36. And the optimal retrofitted HEN with relocation concept 2 is found as shown in Figure 4.37, giving the maximum profit of $1,800,000 in 5 years.

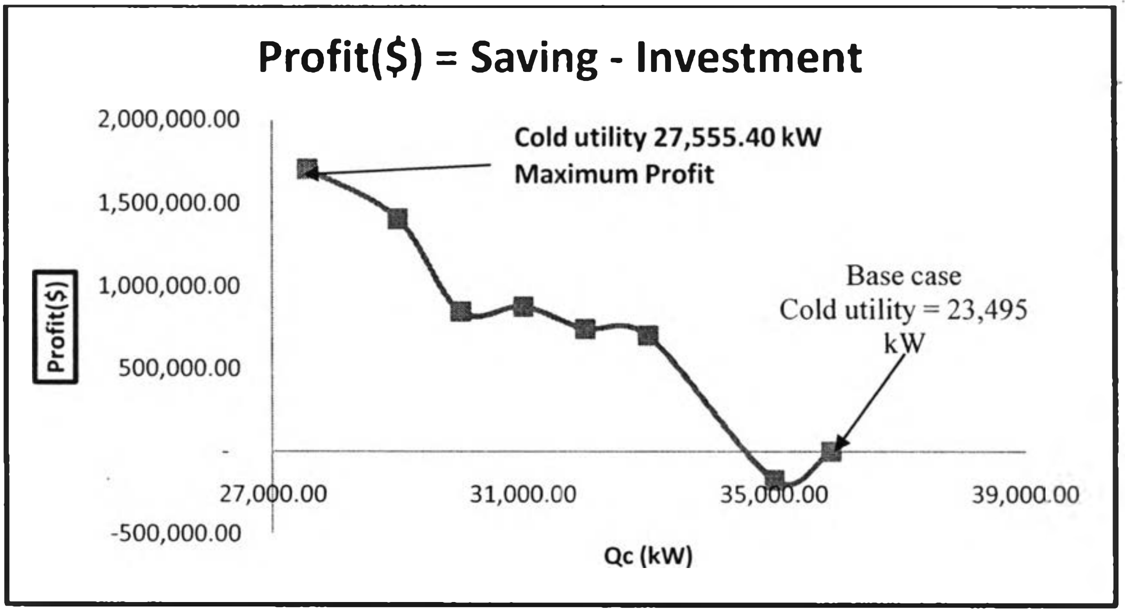

Figure 4.36 Total profit as a function of cold utility in concept 2 of example 4.

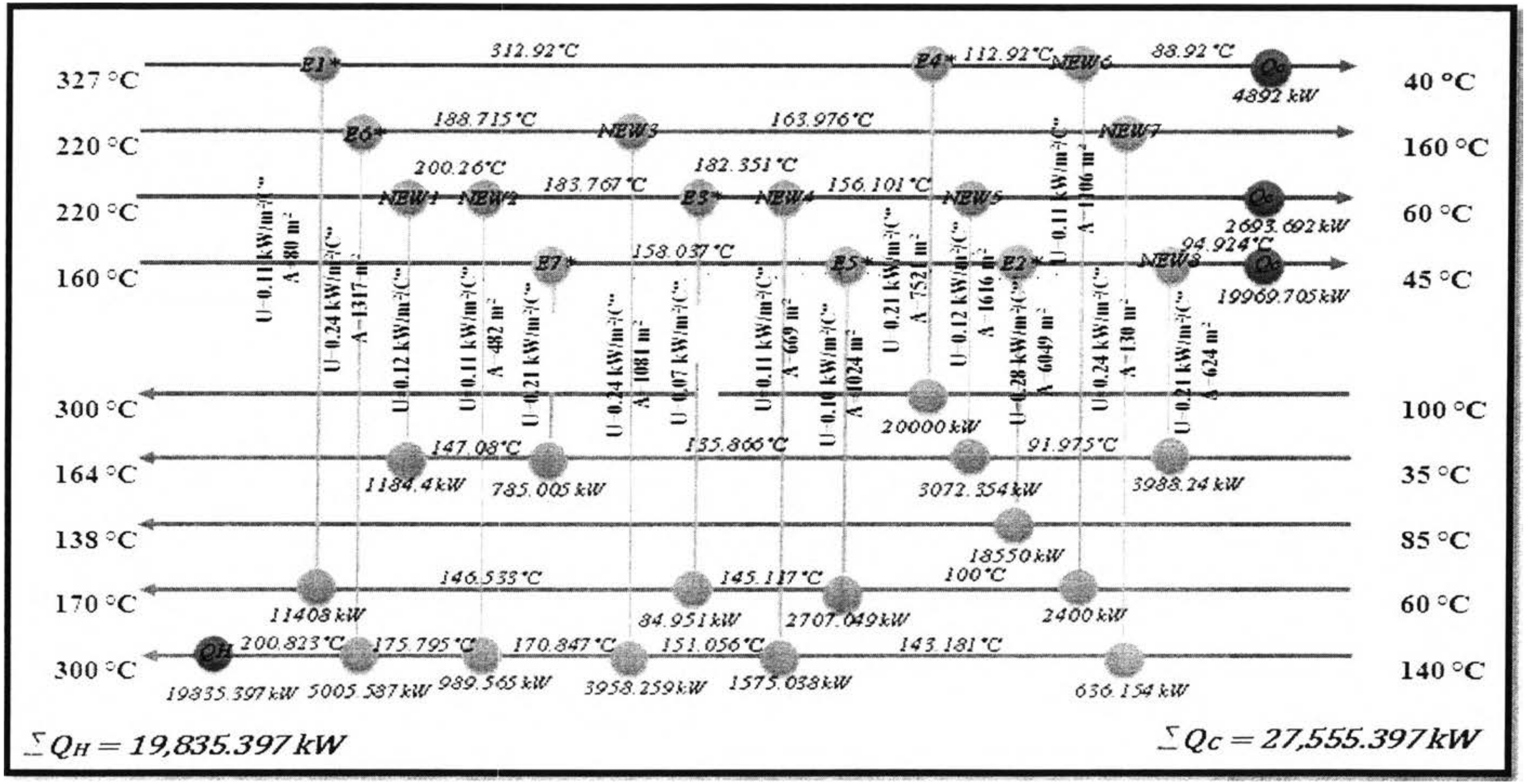

Figure 4.37 Modified network in retrofit design of example 4 in concept 2(nonsplitting and EMAT = 12.92).

The optimal retrofit case consumes hot and cold utilities of 19,835.37 and 27,555.40 kw, respectively, with HRAT = 8 °C, as shown in the composite curves of Figure 4.38.

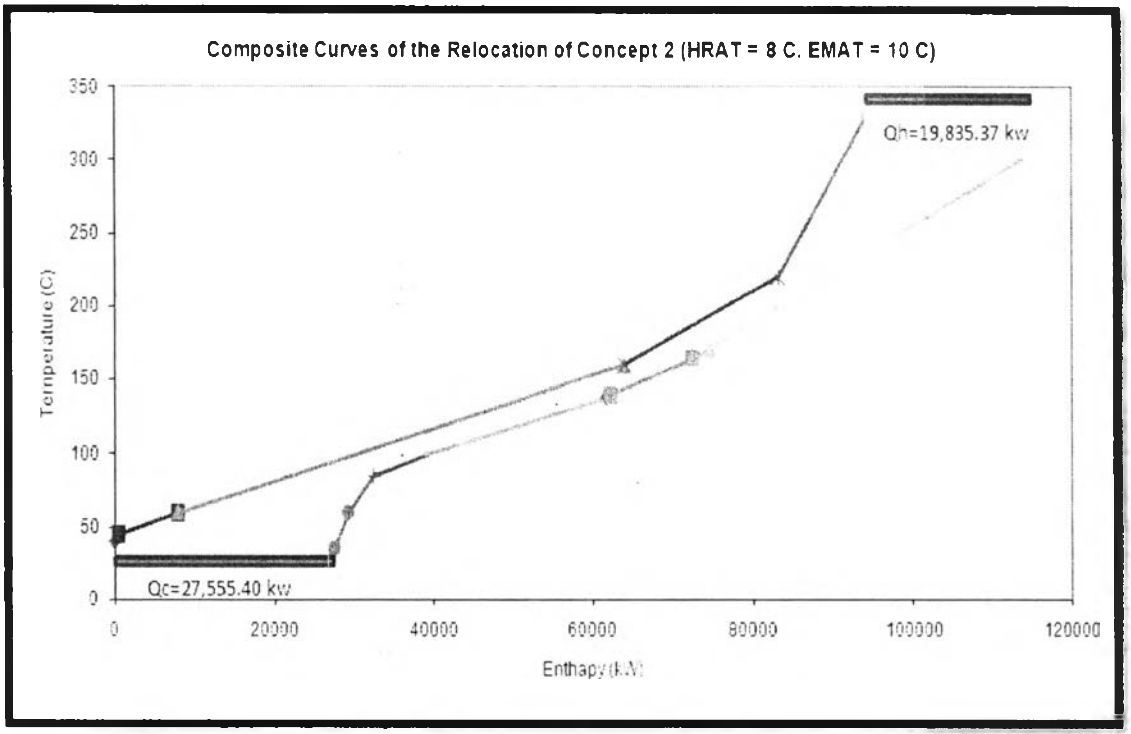

Figure 4.38 Composite curves of the optimal retrofit case with relocation concept 2 of example 4.

Table 4.19 shows the result including heat exchanger area, heat load, additional area and cost of investment of retrofit model of example 4of concept 2.

Table 4.19 Result in retrofit design in concept 2 of example 4

UNIT	Heat Exchanger Area (m^2)	Heat Load (kW)	Additional Area (m^2)	Cost of Additional and Removal Area ($)
E1*=E1+34	80	1408	34	2,380
E2*=E2+2117	6049	18.550	2117	148.190
E3*=E3-1278	33	84.951		
E4*=E4+6623	7521	20.000	6623	463,610
E5*=E5+71	1024	2,707,049	71	4,970
E6*=E6-250	1317	5.005.587		
E7*=E7+47	219	785.005	47	3,290
NEW1	186	1184.4		15.020
NEW2	482	989.565		35,740
NEW3	1081	3.958.259		77.670
NEW4	669	1.575.038		48,830
NEW5	1616	3.072.354		115.120
NEW6	1106	2.400		79,420
NEW7	130	636.154		11.100
NEW8	624	3.988.24		45.680

From the result as shown in Table 4.20 and 4.21, It shows that relocation concept 1 and 2 can reduce the same utility cost (29.63% in hot utility and 23.23% in cold utility) and the same new heat exchanger number but relocation concept 1 has more profit than relocation concept 2. So relocation concept 1 is better in case of no consideration in repiping cost.

Table 4.20 Comparison of all methods of example 4

Options	Additional area requirement [m^2]														
	E1	**E2**	**E3**	**E4**	**E5**	**E6**	**E7**	**New1**	**New2**	**New3**	**New4**	**New5**	**New6**	**New7**	**New8**
Concept1 (Fig 4.34)	**-13**	**2117**	**6**	**183**	**71**	**48**	**14**	**80**	**482**	**218**	**669**	**7521**	**1106**	**130**	**624**
Concept2 (Fig 4.37)	**34**	**2117**	**-1278**	**6623**	**71**	**-250**	**47**	**186**	**482**	**1081**	**669**	**1616**	**1106**	**130**	**624**

Table 4.21 Comparison of all methods of example 4

Options	Additional Area Cost ($)	Utility Consuming				Utility cost ($/yr)	Profit ($)
		Q_H (kW)	Q_H saving (%)	Q_C (kW)	Q_C saving (%)		
Concept1 (Fig 4.34)	**944,857.883**	**19,835.397**	**29.63**	**27,555.397**	**23.26**	**1,355,456.202**	**1,811,448.01**
Concept2 (Fig 4.37)	**1,051,020**	**19,835.397**	**29.63**	**27,555.397**	**23.26**	**1,355,456.202**	**1,705,335.89**

4.5 EXAMPLE 5

The base-case in example 5 as shown in figure 4.39 is light crude preheating train including 18 hot streams and 3 cold streams. This network has 18 heat exchangers. Cold utility is 207.9 kW and hot utility is 75,939 kW. The thermodynamic data can be considered in table 4.22.

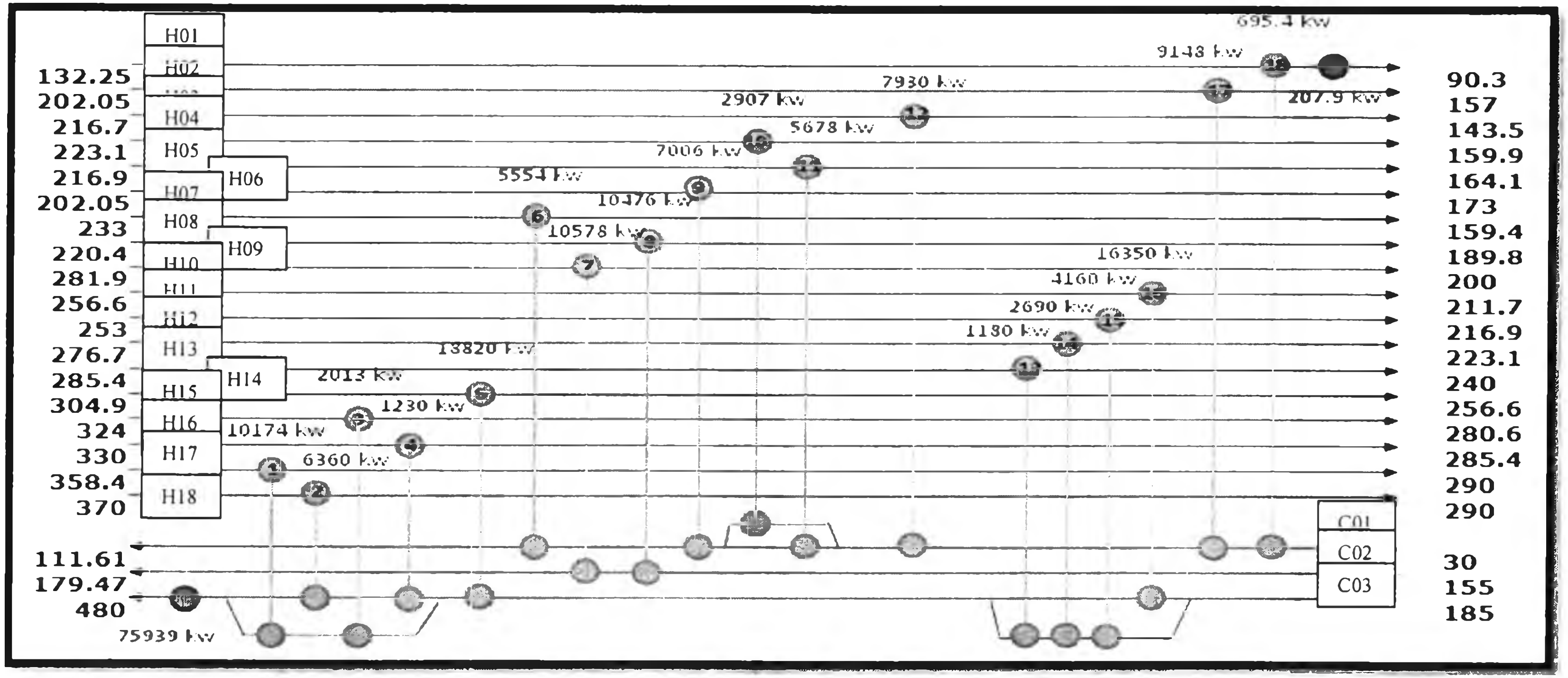

Figure 4.39 Grid diagram of Light Crude in base-case *(EMAT = 3.3 ℃)*.

Table 4.22 Information of base case of example 5

NO. HEAT EXCHANGER	HEAT LOAD (KW)	HEAT EXCHANGER AREA (M^2)	OVERALL HEAT TRANSFER ($KW/M^2/°C$)
1	10174	1424	0.391
2	6360	1028	0.285
3	2013	125	1.03
4	1230	98.2	0.555
5	18820	1374	0.575
6	5554	244	0.262
7	10578	940	0.184
8	10476	441	0.548
9	7006.1	311	0.238
10	2907	70	0.365
11	5678	146	0.343
12	7930	321	0.208
13	1180	147	0.32
14	2690	162	0.662
15	4160	183	0.626
16	16350	1509	0.468
17	288	288	0.23
18	440	441	0.0187

Cost model of new heat exchangers (\$/year): $a + (b \times Area^c)$; $a = 30000$; $b = 750$, $c = 0.81$ (Area unit of m^2).

Cost model of additional heat exchanger (\$/year): $b \times Area^c$; $b = 750$, $c = 0.81$ (Area unit of m^2).

Cost of utilities: HU(stream) = 60 \$/kW/year; CU(cooling water) = 6.0 \$/kW/year.

Economic data: rate of interest = 0%.

The annual hot and cold utility consumption of the existing network is 75,939 kW and 207.9 kW, respectively as shown composite curves of Figure 4.40, corresponding to heat recovery approach temperature (HRAT) = 38 °C and exchanger minimum approach temperature (EMAT) = 3.3 °C.

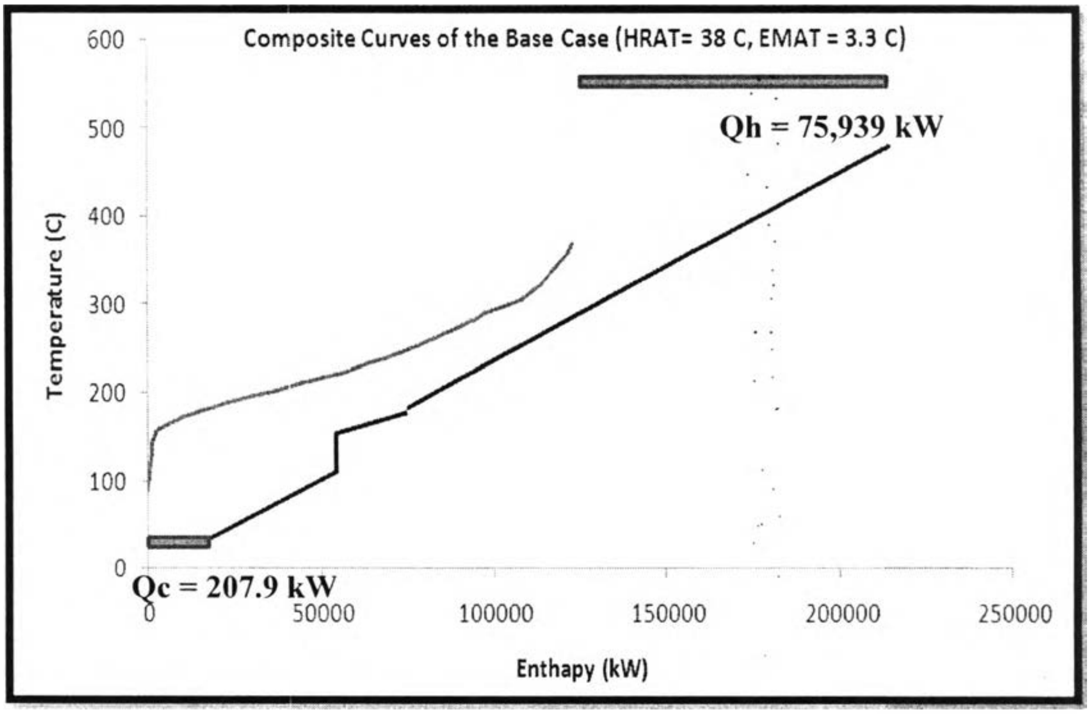

Figure 4.40 Composite curves of the base-case HEN in example 5 (light crude oil).

4.5.1 Retrofit with relocation concept 1 of Example 5

Plot graph between profit($) and hot or cold utility as shown in Figure 4.41. The profit of the retrofit case is calculated by eq.25

The base-case HEN is retrofitted by using retrofit model of GAMS with MILP (Mixed Integer Linear Programming) and the relocation program with concept 1 and 2 using Visual C++. The retrofitted HEN at different HRAT is generated by the retrofit model. Applying the program of the relocation concept 1, the profit of retrofitted HEN at different HRAT (or cold utility) is plotted as shown in Figure 4.41. And the optimal retrofitted HEN with relocation concept 1 is found as shown in figure 4.42, giving the maximum profit of $ 92,000 in 10 years.

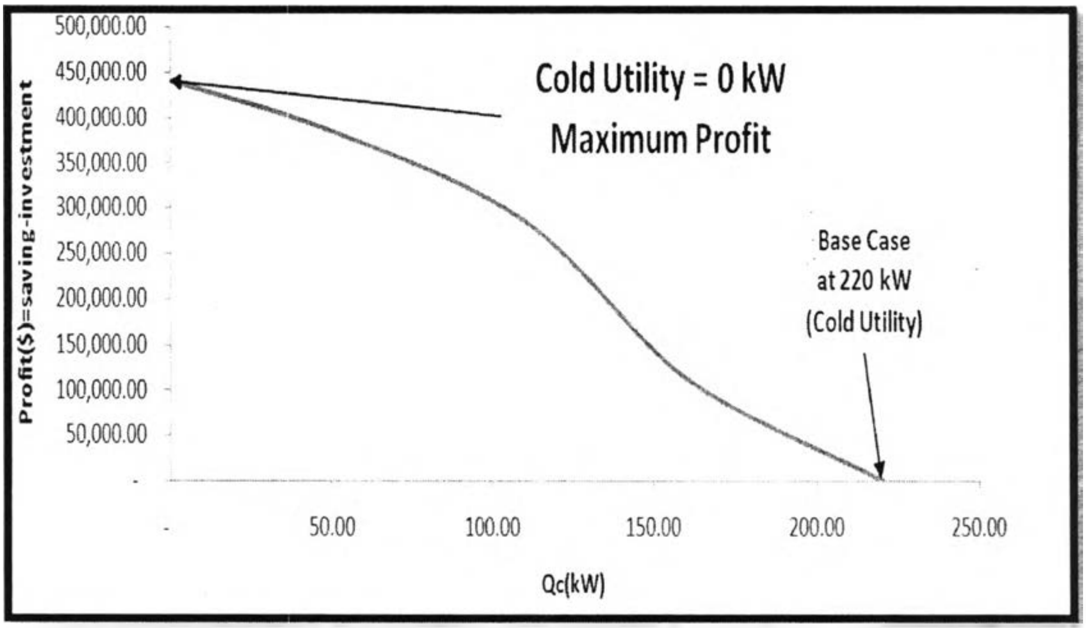

Figure 4.41 Total profit as a function of cold utility in concept 1 of example 5.

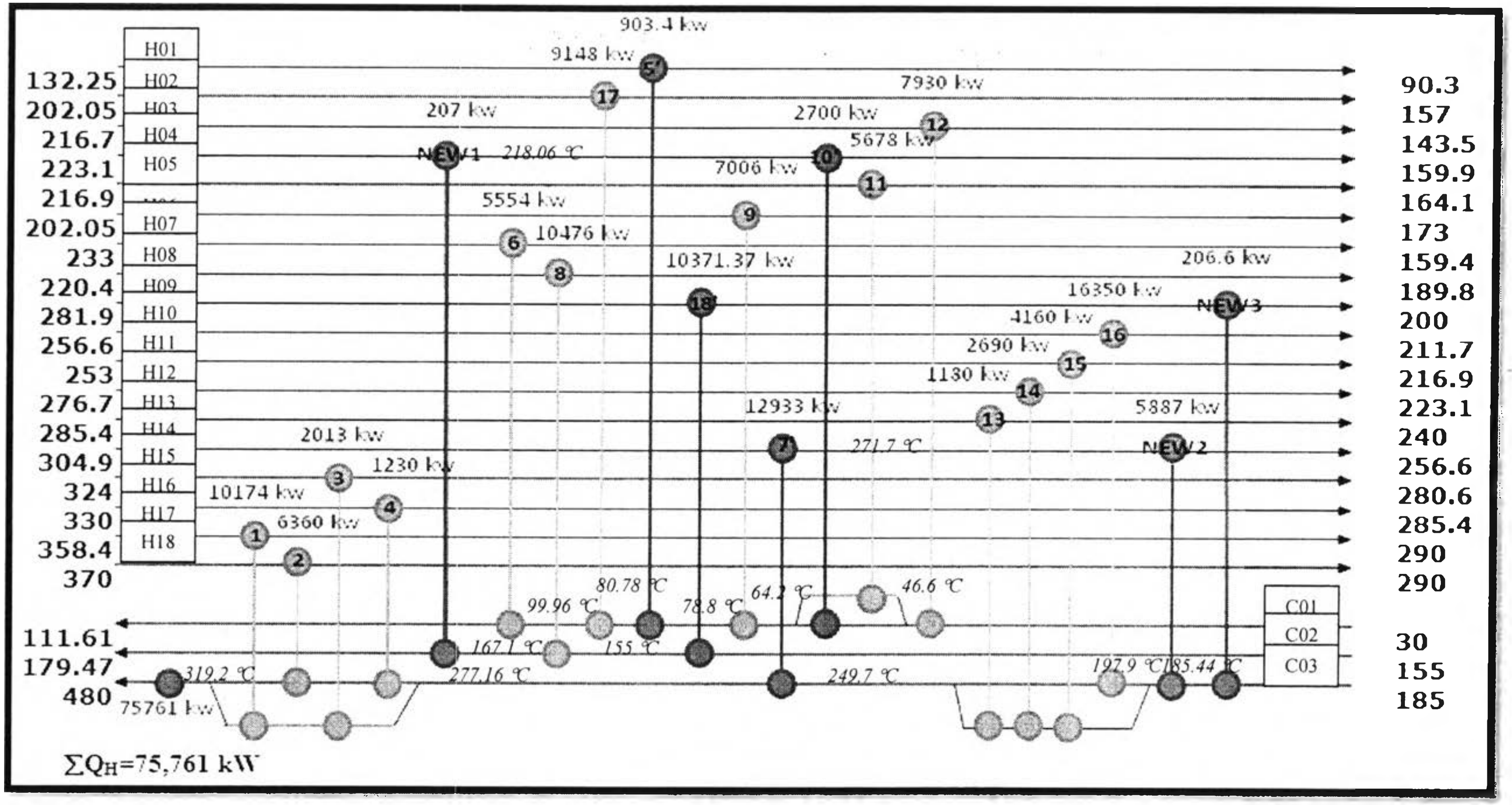

Figure 4.42 Modified network in retrofit design of example 5 in concept 1.

****(nonsplitting and EMAT = 3.3)*

The optimal retrofit case consumes only hot utilities of 75,761 kw with HRAT = 18 °C, as shown in the composite curves of Figure 4.43

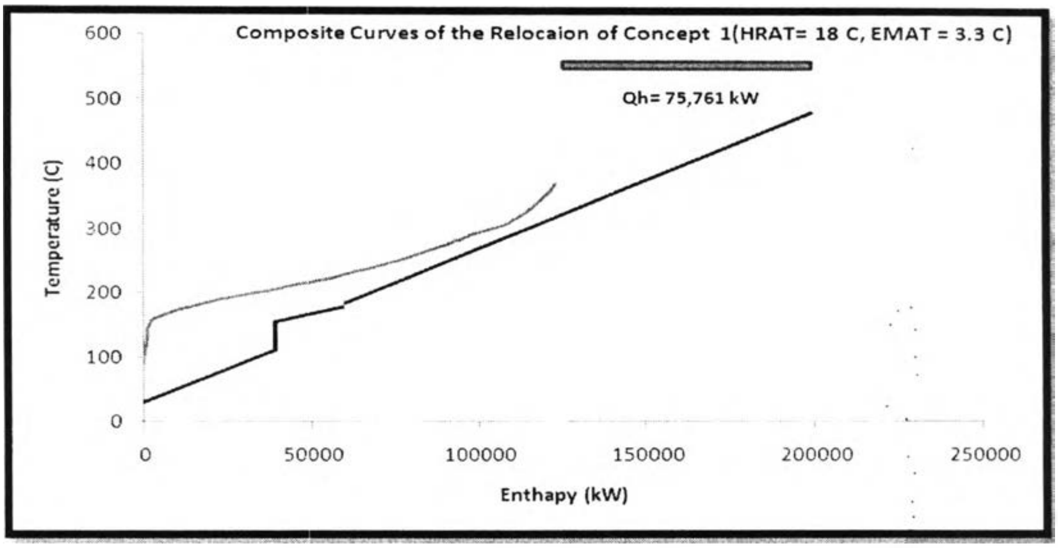

Figure 4.43 Composite curves of the optimal retrofit case with relocation concept 1 of example 5.

Table 4.23 shows the result including heat exchanger area, heat load, additional area and cost of investment of retrofit model of example 5 of concept 1.

Table 4.23 Result in retrofit design in concept 1 of example 5

NO.HEAT EXCHANGER NETWORK	HEAT LOAD (M²)	HEAT EXCHANGER AREA(M²)	ADDITIONAL AREA (M²)
1	10174	1424	-
2	6360	1025	-
3	2013	125	-
4	1230	98.2	-
5'=5-196	12933	1182	-196
6	5554	244	-
7'=7-27	10371	909	-27
8	10476	441	-
9	7006	311	-
10'=10-14	2700	56	-14
11	5678	146	-
12	7930	321	-
13	1180	147	-
14	2690	162	-
15	4160	183	-
16	16350	1509	-
17	9148	288	-
18'=18-300	903.305	741	-300
NEW1	206.712	44	-
NEW2	5887	141	-
NEW3	206.592	133	-

4.5.2 Retrofit with relocation concept 2 of Example 5

For the retrofit case with relocation concept 2, the retrofitted HEN at different HRAT is generated by the retrofit model. Applying the program of the relocation concept 2, the profit of retrofitted HEN at different HRAT (or cold utility) is plotted as shown in Figure 4.44. And the optimal retrofitted HEN with relocation concept 2 is found as shown in Figure 4.45, giving the maximum profit of $ 240,000 in 10 years.

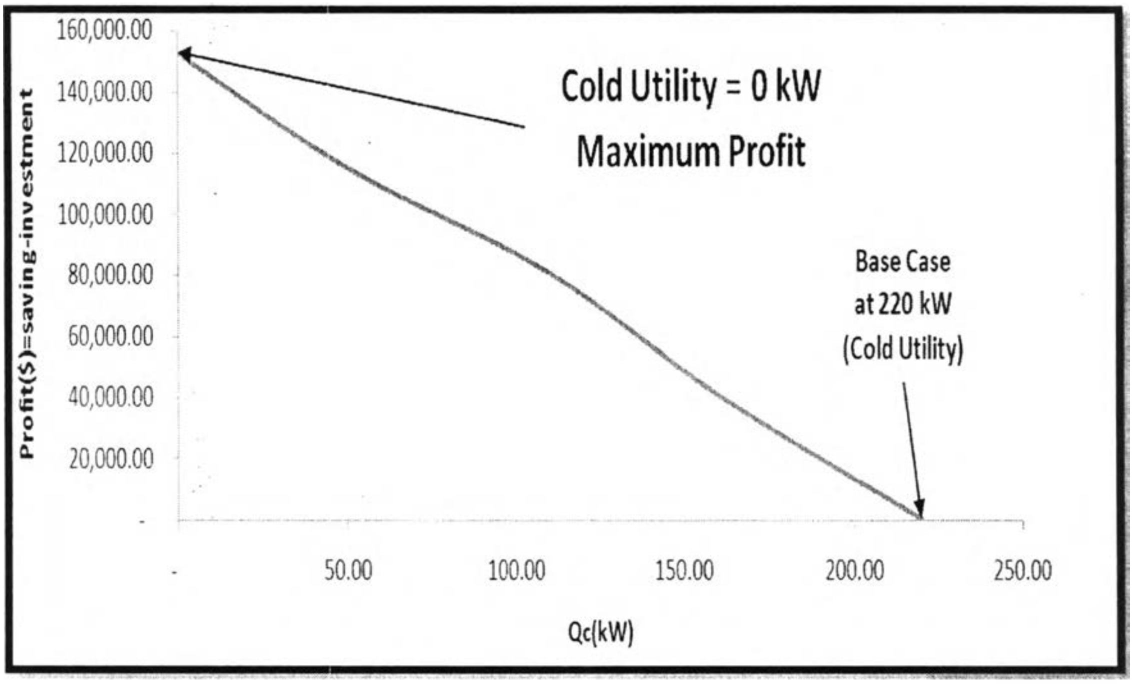

Figure 4.44 Total profit as a function of cold utility in concept 2 of example 5.

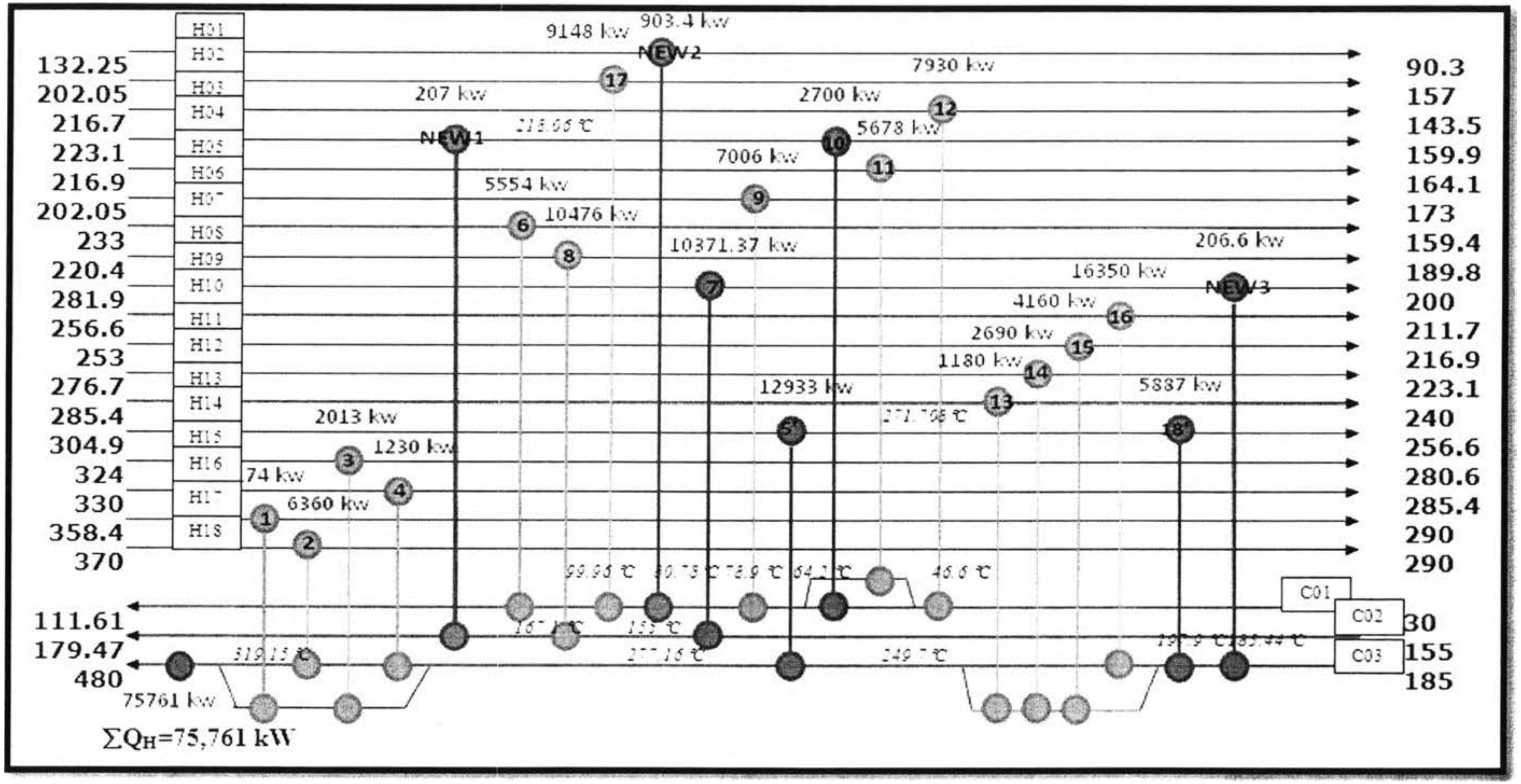

Figure 4.45 Modified network in retrofit design of example 5 in concept 2(nonsplitting and EMAT = 3.3).

The optimal retrofit case consumes only hot utilities of 75,761 kw with HRAT = 18 °C, as shown in the composite curves of Figure 4.46.

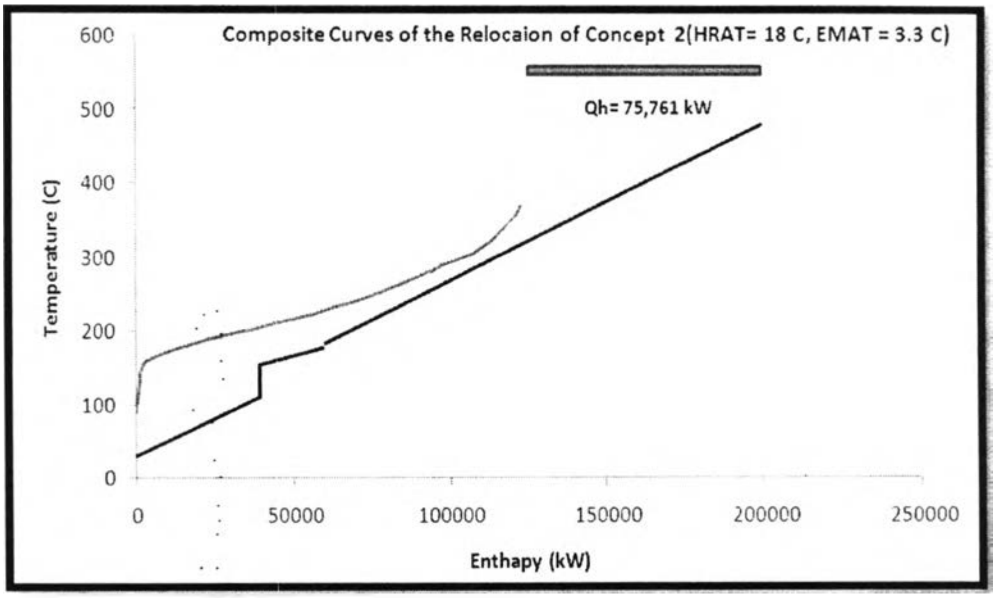

Figure 4.46 Composite curves of the optimal retrofit case with relocation concept 2 of example 5.

Table 4.24 shows the result including heat exchanger area, heat load, additional area and cost of investment of retrofit model of example 5 of concept 2.

Table 4.24 Result in retrofit design in concept 2 of example 5

NO.HEAT EXCHANGER NET-WORK	HEAT LOAD (M^2)	HEAT EXCHANGER AREA(M^2)	ADDITIONAL AREA (M^2)
1	10174	1424	-
2	6360	1028	-
3	2013	125	-
4	1230	98.2	-
5'=5-469	12933	909	-469
6	5554	244	-
7'=7-195	10371	741	-195
8	10476	441	-
9	7006	311	-
10'=10-14	2700	56	-14
11	5678	146	-
12	7930	321	-
13	1180	147	-
14	2690	162	-
15	4160	183	-
16	16350	1509	-
17	9148	288	-
18'=18-301	903	141	-301
NEW1	206.712	44	-
NEW2	5887	1182	-
NEW3	206.592	133	-

From the result as shown in Table 4.25, It shows that relocation concept 1 and 2 can reduce the same utility cost (0.234 % in hot utility saving and 100 % in cold utility saving) and The both retrofit network as shown in Figure 4.42 and 4.45 have the same new heat exchanger number but relocation concept 1 has much more profit than relocation concept 2. So relocation concept 1 is better choice in case of no consideration in repiping cost.

Table 4.25 Comparison of all methods of example 5

Options	Total Area (m^2)	Additional Area Cost ($)	Utility Consuming				Utility cost ($/yr)	Profit ($)
			Q_H (kW)	Q_H saving (%)	Q_C (kW)	Q_C saving (%)		
Base-case (Fig.4.39)	9,251.2	-	75,939	-	207.9	-	4,557,587.4	-
Concept1 (Fig.4.42)	9,633.2	333,351.11	75,761	0.234	0	100	4,545,681.42	440,537.59
Concept2 (Fig.4.45)	9,633.2	621,692.31	75,761	0.234	0	100	4,545,681.42	152,196

4.6 EXAMPLE 6

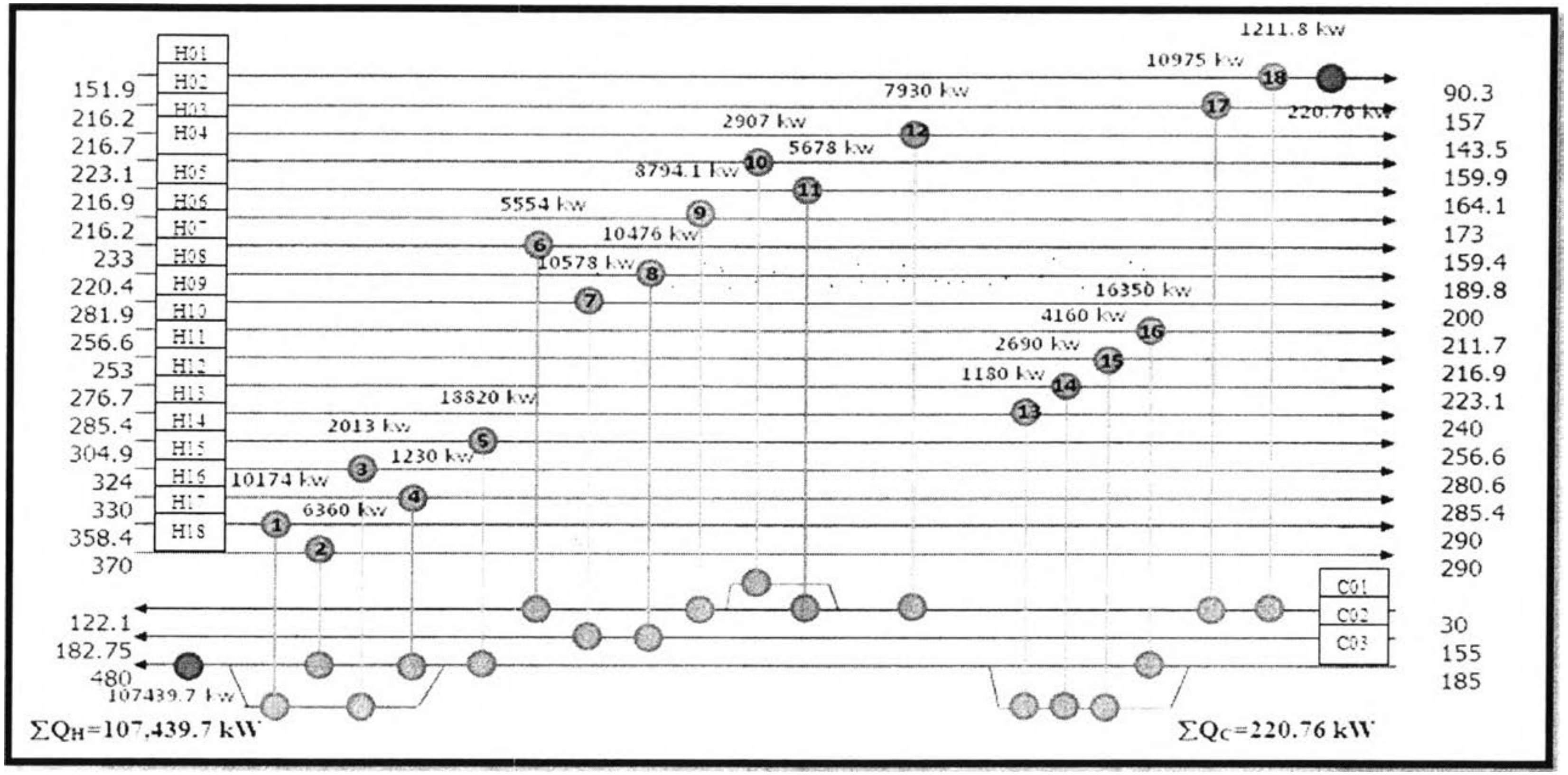

Figure 4.47 Grid diagram of Heavy Crude in base-case *(EMAT = 20.2 °C)*.

The base-case in example 6 as shown in figure 4.47 is heavy crude preheating train including 18 hot streams and 3 cold streams. This network has 18 heat exchangers. Cold utility is 220.76 kW and hot utility is 107,439.7 kW. The thermodynamic data can be considered in table 4.22.

Table 4.26 Information of base case of example 6

NO. HEAT EXCHANGER	HEAT LOAD (KW)	HEAT EXCHANGER AREA (M^2)	OVERALL HEAT TRANSFER (KW/M^2 °C)
1	10174	1424	0.173
2	6360	1028	0.136
3	2013	125	0.297
4	1230	98.2	0.297
5	18820	1374	0.373
6	5554	244	0.3
7	10578	940	0.191
8	10476	441	0.557
9	8794.1	311	0.303
10	2907	70	0.385
11	5678	146	0.362
12	7930	321	0.218
13	1180	147	0.229
14	2690	162	0.519
15	4160	183	0.589
16	16350	1509	0.387
17	10975	288	0.34
18	1211.8	440	0.03

Cost model of new heat exchangers ($/year): a + (b×Area^c); a = 30000; b = 750, c = 0.81 (Area unit of m^2). Cost model of additional heat exchanger ($/year) b×Area^c; b = 750, c = 0.81 (Area unit of m^2).

Cost of utilities: HU(stream) = 60 $/kW.year; CU(cooling water) = 6.0 $/kW.year; Economic data: rate of interest = 0%.

The annual hot and cold utility consumption of the existing network is 107,439.7 kW and 220.76 kW, respectively as shown composite curves of Figure 4.40, corresponding to heat recovery approach temperature (HRAT) = 38 °C and exchanger minimum approach temperature (EMAT) = 3.3 °C.

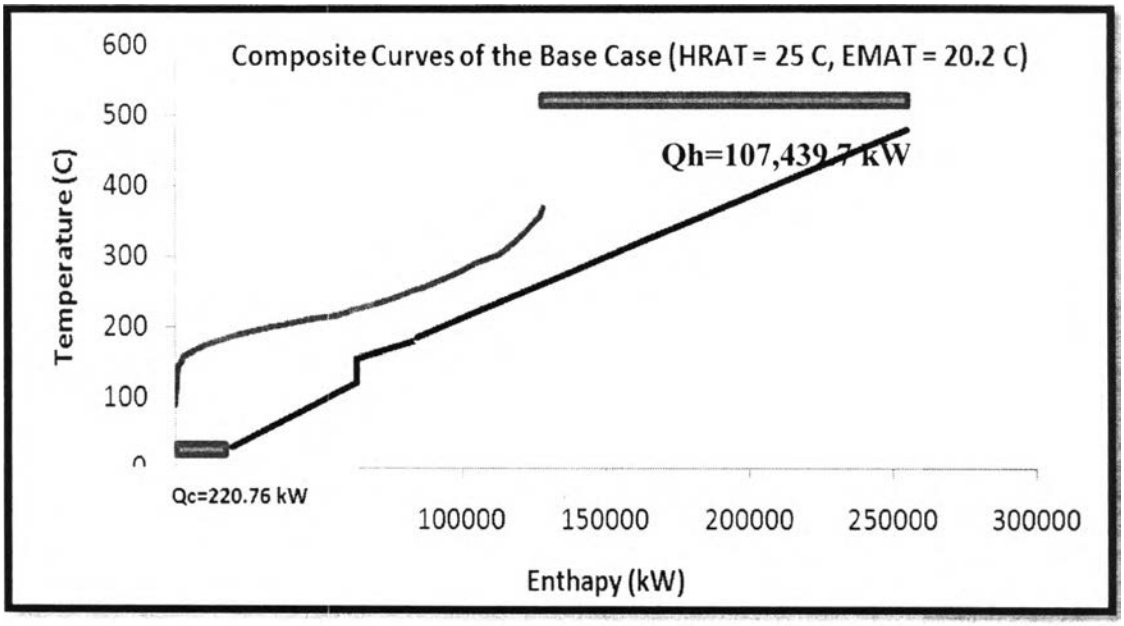

Figure 4.48 Composite curves of the base-case HEN in example 6 (heavy crude oil).

4.6.1 Retrofit with relocation concept 1 of Example 6

Plot graph between profit($) and hot or cold utility as shown in Figure 4.49. The profit of the retrofit case is calculated by eq.25

The base-case HEN is retrofitted by using retrofit model of GAMS with MILP (Mixed Integer Linear Programming) and the relocation program with concept 1 and 2 using Visual C++. The retrofitted HEN at different HRAT is generated by the retrofit model. Applying the program of the relocation concept 1, the profit of retrofitted HEN at different HRAT (or cold utility) is plotted as shown in Figure 4.49. And the optimal retrofitted HEN with relocation concept 1 is found as shown in figure 4.50, giving the maximum profit of $ 92,000 in 10 years.

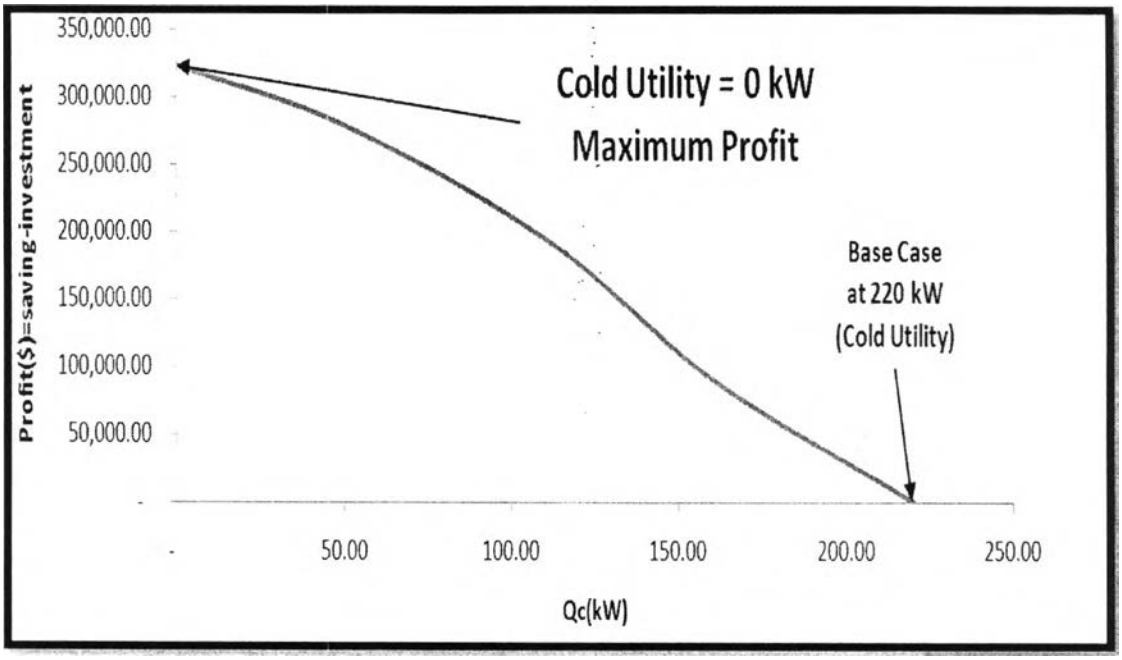

Figure 4.49 Total profit as a function of cold utility in concept 1 of example 6.

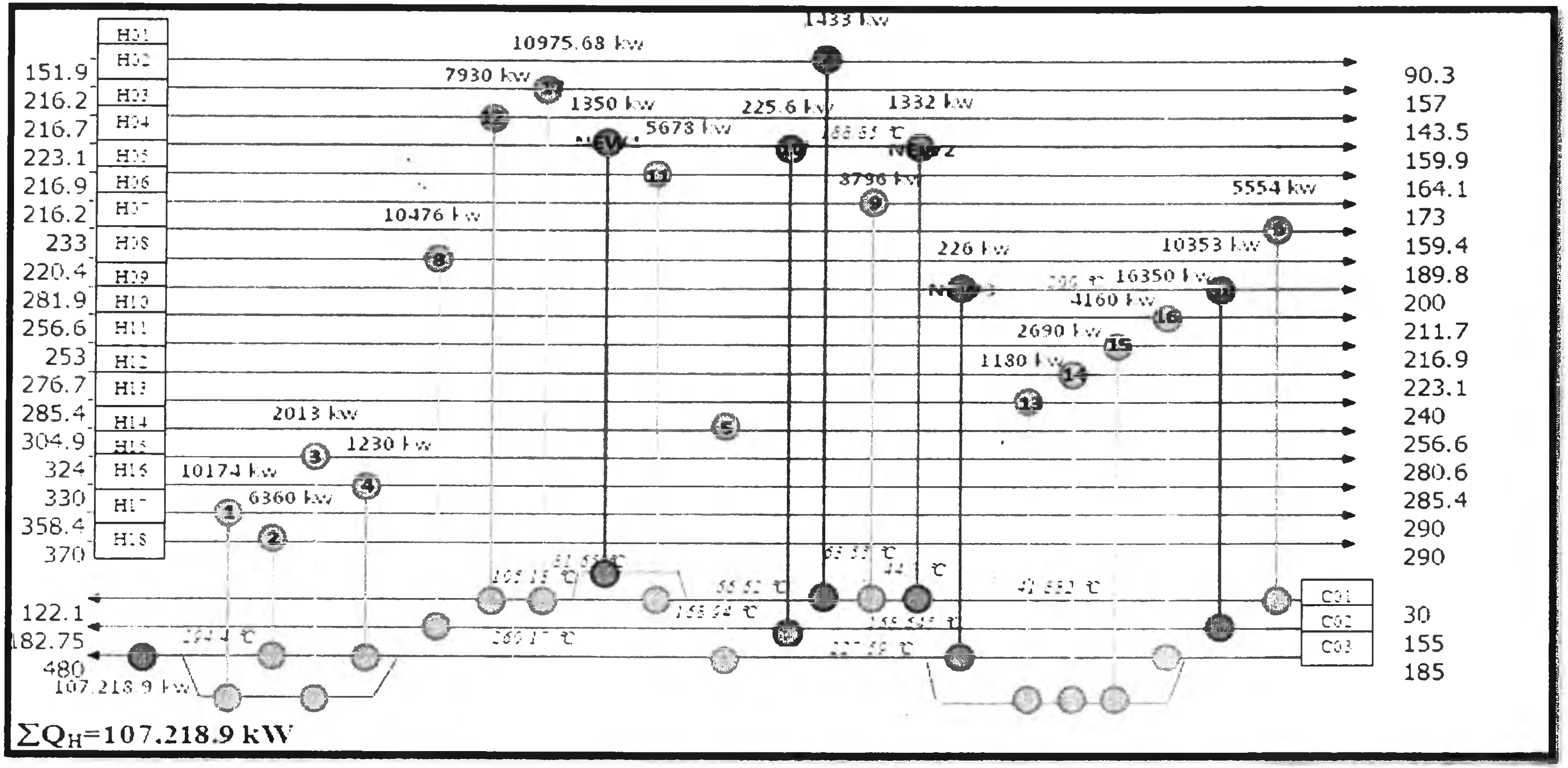

Figure 4.50 Modified network in retrofit design of example 6 in concept 1(nonsplitting and EMAT = 20.2).

The optimal retrofit case consumes only hot utilities of 107,218.9 kw with HRAT = 12 °C, as shown in the composite curves of Figure 4.51.

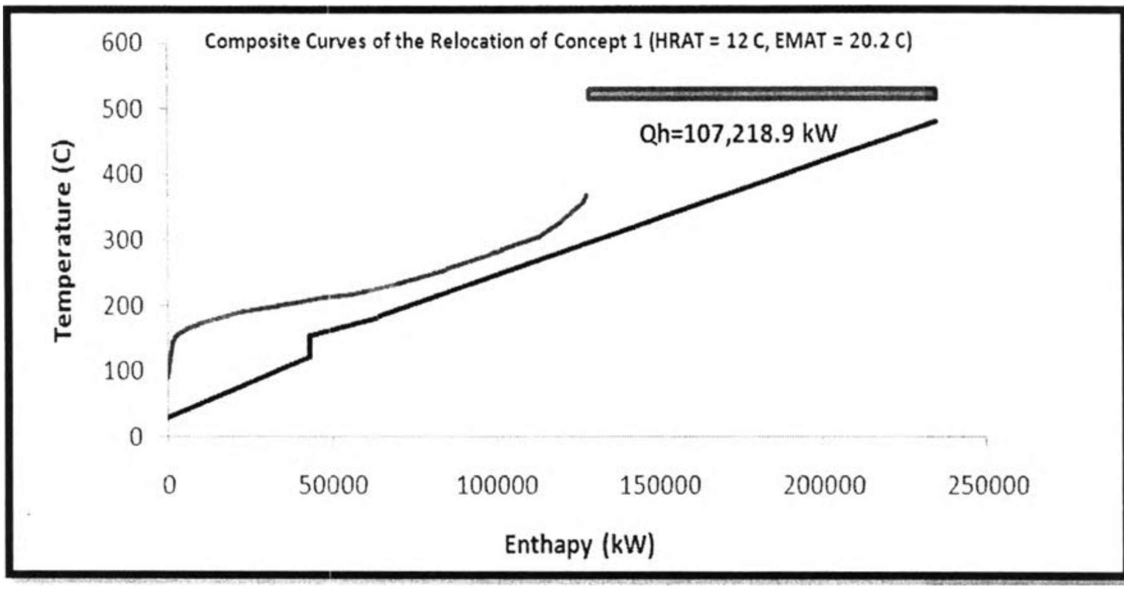

Figure 4.51 Composite curves of the optimal retrofit case with relocation concept 1 of example 6.

Table 4.27 shows the result including heat exchanger area, heat load, additional area and cost of investment of retrofit model of example 6 of concept 1.

Table 4.27 Result in retrofit design in concept 1 of example 6

NO.HEAT EXCHANGER NETWORK	HEAT LOAD (M^2)	HEAT EXCHANGER AREA(M^2)	ADDITIONAL AREA (M^2)
1	10174	1424	-
2	6360	1028	-
3	2013	125	-
4	1230	98.2	-
5	18820	137	-
6	5554	244	-
7'=7+8	1433	953	+8
8	10476	441	-
9	7006	311	-
10'=10+30	225.6	101	+30
11	5678	146	-
12	7930	321	-
13	1180	147	-
14	2690	162	-
15	4160	183	-
16	16350	1509	-
17	9148	288	-
18'=18+249	10353	688	+249
NEW1	1350	25	-
NEW2	1332	26	-
NEW3	226	31	-

4.6.2 Retrofit with relocation concept 2 of Example 6

For the retrofit case with relocation concept 2, the retrofitted HEN at different HRAT is generated by the retrofit model. Applying the program of the relocation concept 2, the profit of retrofitted HEN at different HRAT (or cold utility) is plotted as shown in Figure 4.44. And the optimal retrofitted HEN with relocation concept 2 is found as shown in Figure 4.45, giving the maximum profit of $ 240,000 in 10 years.

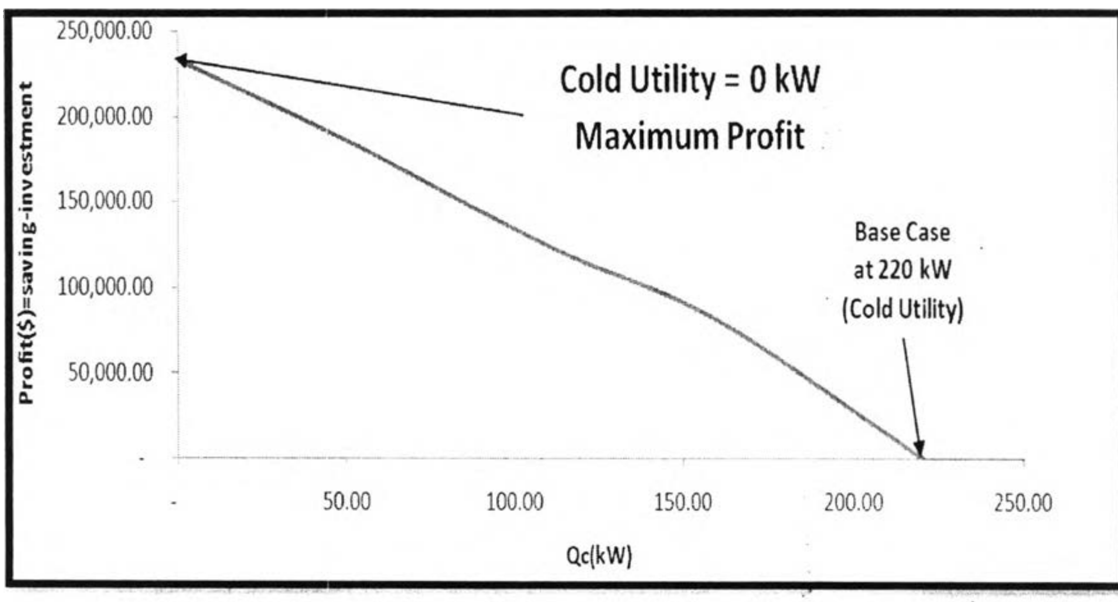

Figure 4.52 Total profit as a function of cold utility in concept 2 of example 6.

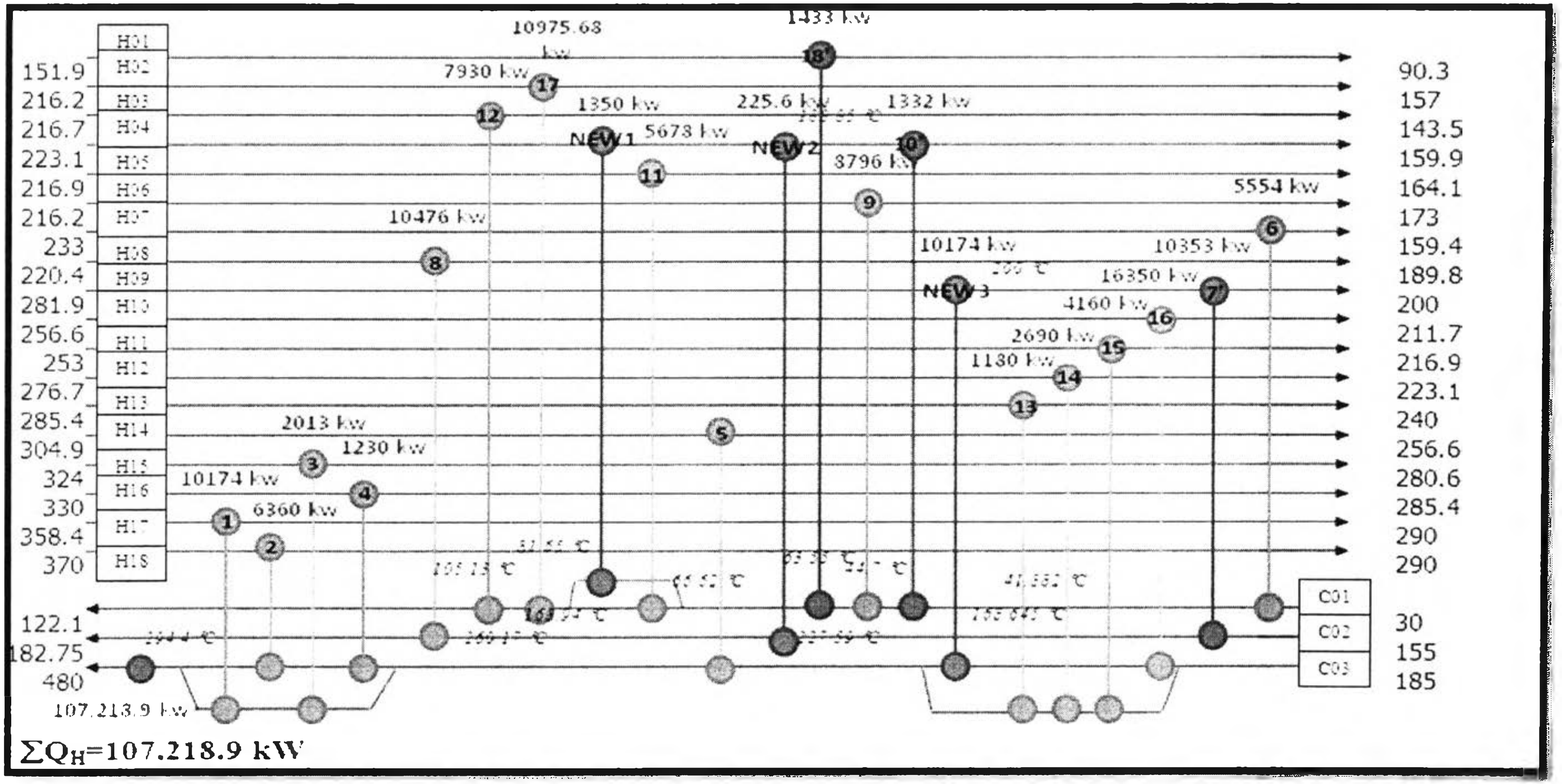

Figure 4.53 Modified network in retrofit design of example 6 in concept 2(nonsplitting and EMAT = 20.2).

The optimal retrofit case consumes only hot utilities of 75,761 kw with HRAT = 18 °C, as shown in the composite curves of Figure 4.54.

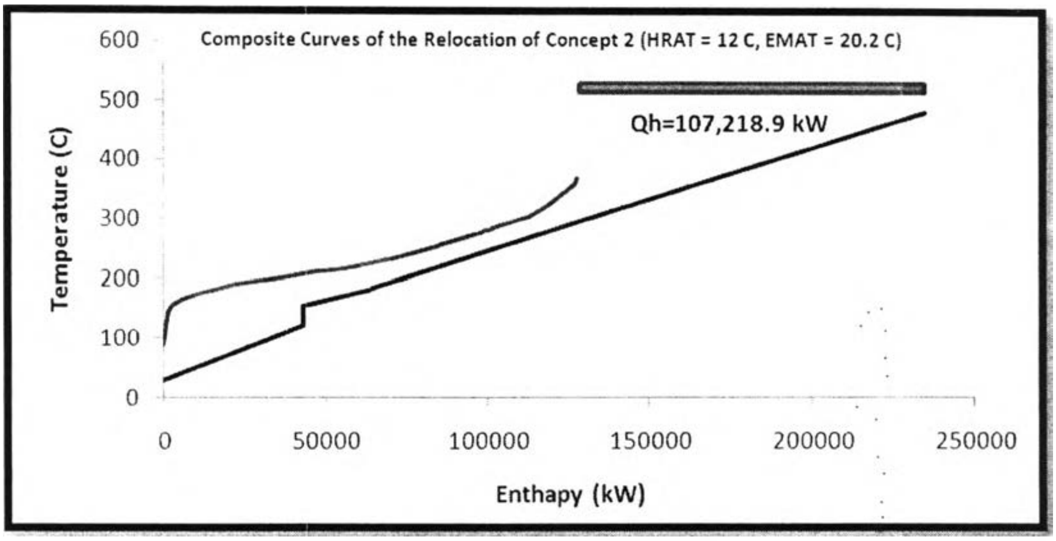

Figure 4.54 Composite curves of the optimal retrofit case with relocation concept 2 of example 6.

Table 4.28 shows the result including heat exchanger area, heat load, additional area and cost of investment of retrofit model of example 6 of concept 2.

Table 4.28 Result in retrofit design in concept 2 of example 6

NO.HEAT EXCHANGER NETWORK	HEAT LOAD (M²)	HEAT EXCHANGER AREA(M²)	ADDITIONAL AREA (M²)
1	10174	1424	-
2	6360	1028	-
3	2013	125	-
4	1230	98.2	-
5	18820	137	-
6	5554	244	-
7'=7-257	10353	688	-257
8	10476	441	-
9	7006	311	-
10'=10-44	1332	26	-44
11	5678	146	-
12	7930	321	-
13	1180	147	-
14	2690	162	-
15	4160	183	-
16	16350	1509	-
17	9148	288	-
18'=18-515	1433	953	-515
NEW1	1350	25	-
NEW2	226	101	-
NEW3	10174	31	-

From the result as shown in Table 4.29, It shows that relocation concept 1 and 2 can reduce the same utility cost (0.205 % in hot utility saving and 100 % in cold utility saving) and The both retrofit network as shown in Figure 4.50 and 4.53 have the same new heat exchanger number but relocation concept 1 has more profit than relocation concept 2. So relocation concept 1 is better choice in case of no consideration in repiping cost.

Table 4.29 Comparison of all methods of example 6

Options	Total Area (m^2)	Additional Area Cost ($)	Utility Consuming				Utility cost ($/yr)	Profit ($)
			Q_H (kW)	Q_H saving (%)	Q_C (kW)	Q_C saving (%)		
Base-case (Fig.4.47)	9,191	-	107,439.7	-	220.76	-	6,447,707	-
Concept1 (Fig.4.50)	9,565	204,106.4	107,219	0.205	0	100	6,433,080	323,487.23
Concept2 (Fig.4.53)	9,929	344,262.6	107,219	0.205	0	100	6,433,080	233,003.77