CHAPTER IV
RESULTS AND DISCUSSION

4.1 Water Network (WN) Design

4.1.1 Case study 1.1 : Simple fixed-flowrate problem (Prakash *et al.*, 2005a)

From water fixed-flowrate problem which is shown before in background and literature review section is picked up to apply with mathematical program. The data is shown in Table 4.1. There have four processes with four source streams and four sink streams. Source streams indicate waste streams emit from each process, and sink streams indicate inlet streams with specified concentration. Without applying water network, it consumes 300 t/h of freshwater and discharges 280 t/h of wastewater. Minimum freshwater flowrate and wastewater flowrate are identified by water cascade analysis (WCA) and water composite curve (WCC) shown in Table 4.2 and Fig. 4.1. From WCA method, amount of freshwater and wastewater are 70 t/h and 50 t/h, respectively (FC_k value at the first row and last low). WCC shows the same result as WCA. The water network for this case is previously shown in Fig. 2.11 by NNA principal.

Table 4.1 Sinks and sources data for Case study 1.1 (Prakash *et al.*, 2005a)

Process	Water sinks, j	Flowrate, FK_j	Concentration, CK_i	Water Sources, i	Flowrate, FS_i	Concentration, CS_i
		(t/h)	(ppm)		(t/h)	(ppm)
1	1	50	20	1	50	50
2	2	100	50	2	100	100
3	3	80	100	3	70	150
4	4	70	200	4	60	250

Table 4.2 Water cascade table for Case study 1.1

k	C_k	F_j	F_i	F_i-F_j	FC_k	Δm_k	Cum.Δm_k	FW_k
					70			
1	0			0				
					70	1400		
2	20	50		-50			1400	70
					20	600		
3	50	100	50	-50			2000	40
					-30	-1500		
4	100	80	100	20			500	5
					-10	-500		
5	150		70	70			0	0
					60	3000		
6	200	70		-70			3000	15
					-10	-500		
7	250		60	60			2500	10
					50	49987500		
8	1000000			0			539227421	539.227

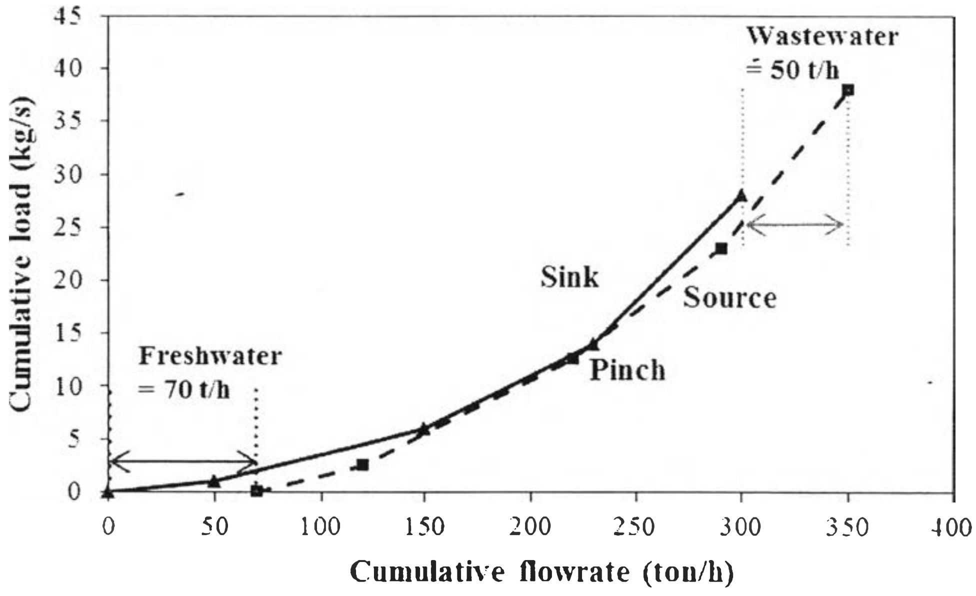

Figure 4.1 Water composite curves for case study 1.1.

After applied the MILP mathematical model (Eq. 3.1-3.13) by GAMS without cost included (CostF =1 \$/t, CostW =1 \$/t, CP =1 stream·h), the result is according to WCA and WCC. Sources which have higher concentration level will transfer contaminant at appropriated splitting flowrate and combined with minimum amount of freshwater to generated sinks at their specified concentration. Amount of freshwater used at each sink (FW_j), concentration of sink (CK_j) and wastewater generate of source (WW_i) are shown in Table 4.3. Mass transfer from sources (i) to sinks (j) shown in Table 4.4 that outcome is water reuse/recycle network shown in Fig. 4.2 represented in grid diagram and process flow diagram. GAMS code is shown in appendix A-1 and the result from GAMS is shown in appendix B-1. Compare with network by NNA principal (Fig. 2.11), The same amount of freshwater and wastewater flowrate are consumed and discharged . There have three matching flowrate from freshwater to sinks (j1, j2 and j3) consume freshwater at 40, 25 and 5 t/h, respectively but MILP generate a lower mathcing network. There are two sink (j1 and j2) that require freshwater at 30 and 40 t/h, respectively.

Table 4.3 Minimum freshwater and wastewater of case study 1.1 by GAMS

Sink, j	**1**	**2**	**3**	**4**	**OFW**
FW_j (t/h)	30	40	0	0	**70**
CK_j (ppm)	20	50	100	200	
Source, i	**1**	**2**	**3**	**4**	**OWW**
WW_i (t/h)	0	0	25	25	**50**

Table 4.4 Transfer flow rate, $F_{i,j}$ (t/h) from source (i) to sink (j) by GAMS

Sink, j / Source, i	1	2	3	4
1	20	30	-	-
2	-	20	80	-
3	-	10	-	35
4	-	-	-	35

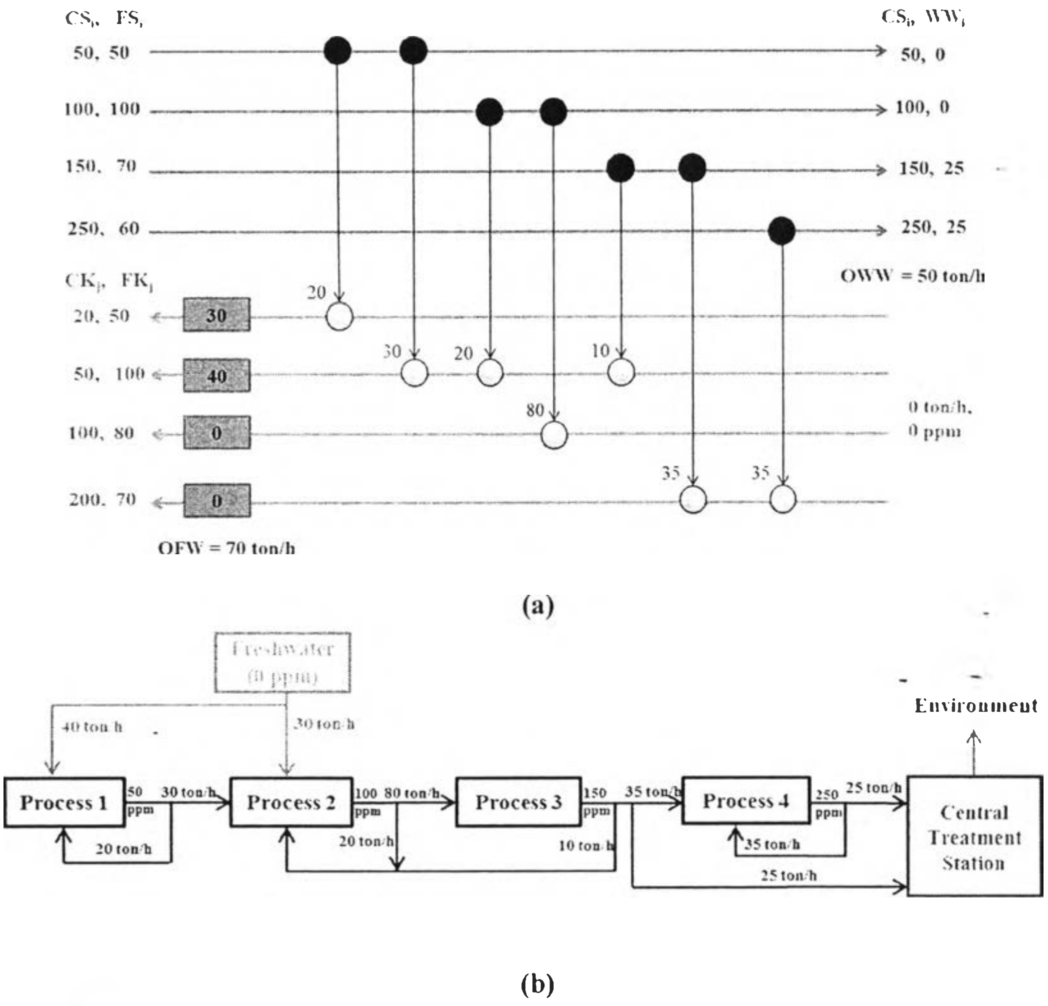

Figure 4.2 Water network of case study 1.1 by GAMS in (a) grid diagram, (b) process flow diagram.

4.1.2 Case study 1.1a : Simple fixed-flowrate problem with cost included 1

This case aim to generate water network to minimize overall cost of freshwater, waste treatment cost before discharge, and piping cost. Each section cost will dominate to the outcome water network. The data of sink and source are same as case 1.1 as shown in Table 4.1. This case still concern single source of freshwater with zero ppm. Wastewater from excess sources will be treated before discharge at constant price. Source and freshwater is transferred to sink and source is transferred to treat by piping and pumping at fixed rate. Cost of freshwater (CostF) is 10 \$/t, cost of waste treatment (CostW) is 100 \$/t, and cost of piping (CP) is 10 \$/ stream·h.

After applied MILP mathematical model (Eq. 3.1-3.13) to this data, the outcome network is same as case 1.1 because the network is the minimum freshwater flowrate and wastewater flowrate network. The cost of freshwater and treatment are minimized at lowest flowrate of freshwater and waste. Piping cost does not impact to the network because it cost is lower than freshwater and treat cost. The oveall cost is 5790 \$/h by 70 t/h of freshwater and 50 t/h of wastewater and 11 streams as see in Fig. 4.2. GAMS code is shown in appendix A-2 and the result from GAMS is shown in appendix B-2.

4.1.3 Case study 1.1b : Simple fixed-flowrate problem with cost included 2

For other scenario, the data of sink and source are same as case 1.1 as shown in Table 4.1. This case still concern single source of freshwater with zero ppm. Wastewater from excess sources will be treated before discharge at constant price. Source and freshwater is transferred to sink and source is transferred to treat by piping and pumping at fixed rate. Cost of freshwater (CostF) is 1 \$/t, cost of waste treatment (CostW) is 10 \$/t, and cost of piping (CP) is 500 \$/stream·h. For this case, piping cost is much higher than freshwater and treat cost that will impact to the result network to generate lower streams of source to sink or freshwater to sink or source to treatment.

After applied MILP mathematical model (Eq. 3.1-3.13) to this data, the outcome network is difference from previous case shown in Fig. 4.2 in grid diagram. The network try to have lower streams because of high piping cost by increase freshwater flowrate and unused source. The oveall cost is 5753.333 $/h by 86.667 t/h of freshwater and 66.667 t/h of wastewater and 10 streams. GAMS code is shown in appendix A-3 and the result from GAMS is shown in appendix B-3.

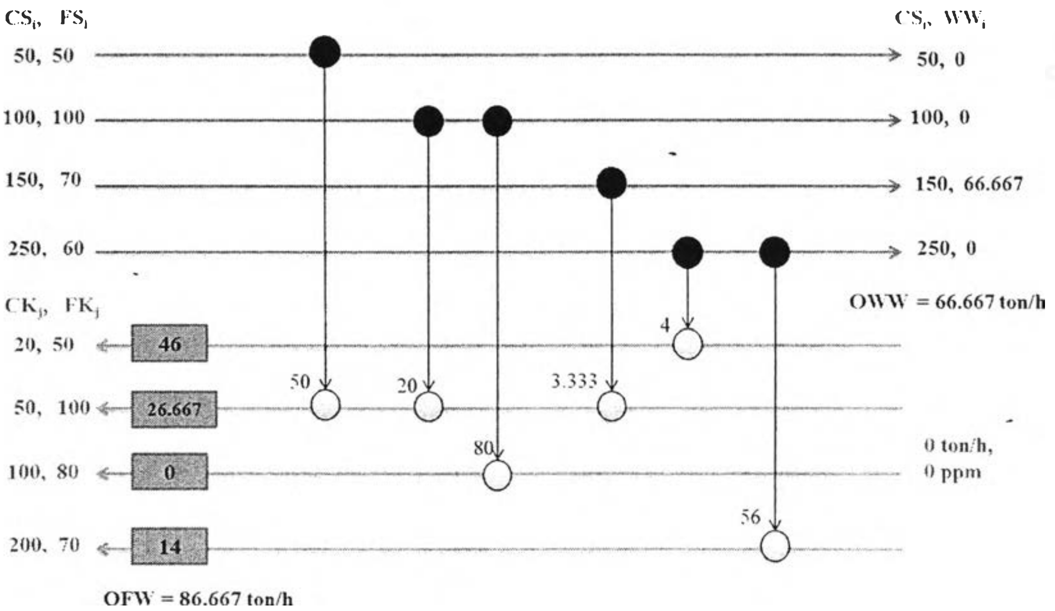

Figure 4.3 Water network of case study 1.1b by GAMS in grid diagram.

4.1.4 Case study 1.1c : Simple fixed-flowrate problem with several freshwater sources

For other scenario, the data of sink and source are same as case 1.1 as shown in Table 4.1. This case consider multiple sources of freshwater with several concentration and cost. This case propose to let the model choose the most economical source of freshwater for the minimum cost network. There are three sources of freshwater concentration (ConF) consist of 0, 20 and 50 ppm where cost (CostF) is 100, 50 and 0 \$/t, respectively. Cost of waste treatment (CostW) is 100 \$/t, and cost of piping (CP) is 10 \$/stream·h.

After applied MILP mathematical model (Eq. 3.14-3.24) to this data, the proper source of freshwater is 20 ppm with 50 \$/t. The result network is shown in Fig. 4.4 in grid diagram. Because of very high cost of zero ppm freshwater source, the model will choose the other source for less cost of network. Eventhough 50 ppm freshwater source is free of cost, it is not chosen cause the network will have more waste stream to treat. The oveall cost is 10287.5 \$/h by 81.25 t/h of 20 ppm freshwater source and 61.25 t/h of wastewater and 10 splitter. GAMS code is shown in appendix A-4 and the result from GAMS is shown in appendix B-4.

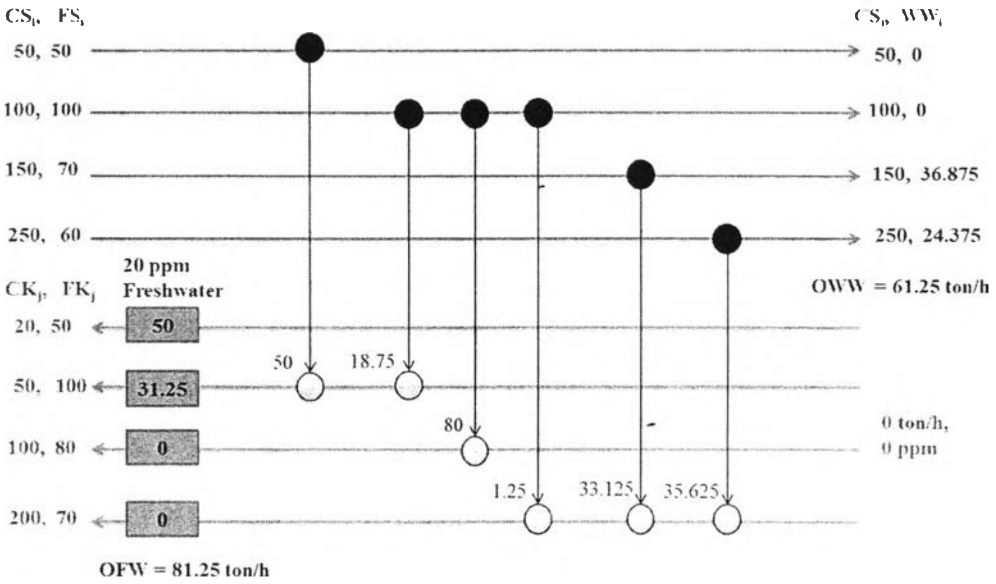

Figure 4.4 Water network of case study 1.1c by GAMS in grid diagram.

4.1.5 Case study 1.2 : Fixed-flowrate problem with zero freshwater and wastewater (Foo, 2008)

From water reuse/recycle process example shown in Table 4.5, there have five source streams and five sink streams from different seven units. This example process is shown in Fig. 4.5. The original process consumes 40.5 t/h of freshwater and discharge wastewater at the same value. Freshwater reduction possibility is identified by WCA shown in Table 4.6 and WCC shown in Fig. 4.6. The resulting freshwater requires and wastewater discharge are both zero (FC_k value at the first row and last low) for this case. Water reuse/recycle generated by NNA principal is shown in Fig. 4.7 and Fig. 4.8 in grid diagram.

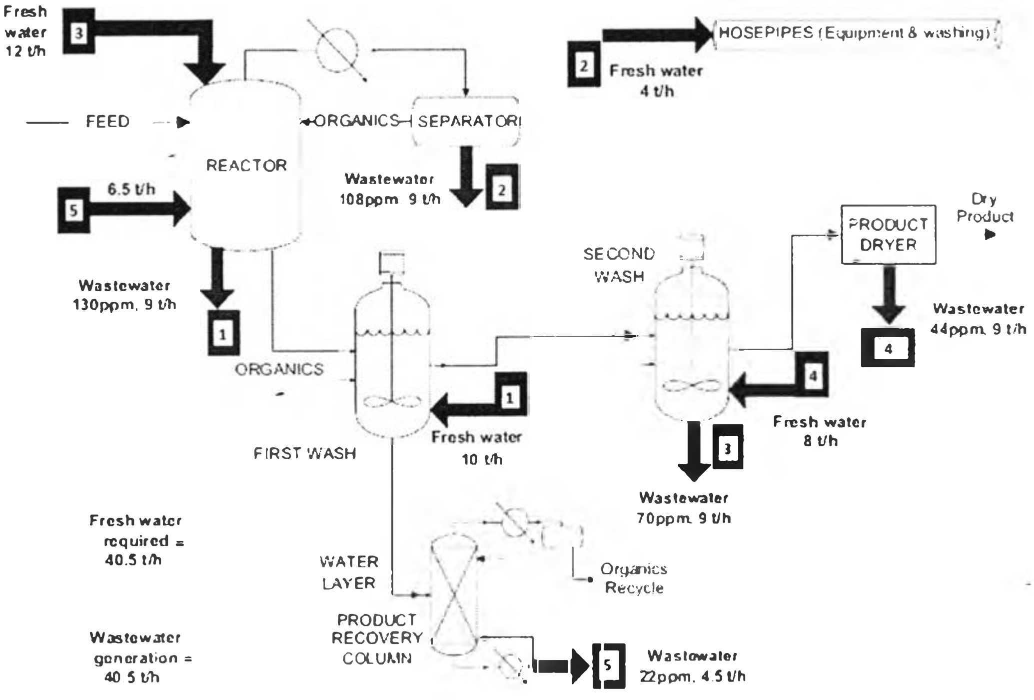

Figure 4.5 Process diagram of case study 1.2 (Foo, 2008).

Table 4.5 Case study 1.2 data (Foo, 2008)

j	Water sinks	Flowrate, FK_i	Concentration, CK_i	i	Water sources	Flowrate, FS_i	Concentration CS_i
		(t/h)	(ppm)			(t/h)	(ppm)
1	First wash	10	127.8	1	Reactor discharge	9	130
2	Hosepipe	4	108	2	Separator	9	108
3	Reactor	12	63.002	3	Second wash	9	70
4	Second wash	8	62.975	4	Dryer	9	44
5	Stream	6.5	45.72	5	Column bottom	4.5	22

Table 4.6 Water cascade table for case study 1.2 (Foo, 2008)

k	C_k	F_i	F_i	F_i-F_j	FC_k	Δm_k	Cum.Δm_k	FW_k
					0			
1	0			0				
					0	0		
2	22		4.5	4.5			0	**0**
					4.5	99		
3	44		9	9			99.00000	2.25000
					13.5	23.22		
4	45.72	6.5		-6.5			122.22000	2.67323
					7	120.785		
5	62.975	8		-8			243.00500	3.85875
					-1	-0.02667		
6	63.002	12		-12			242.97833	3.85670
					-13	-90.97829		
7	70		9	9			152.00004	2.17143
					-4	-152		
8	108	4	9	5			0.00004	3.704E-07
					1	19.8		
9	127.8	10		-10			19.80004	0.15493
					-9	-19.8		
10	130		9	9			0.00004	3.077E-07
					0	0		
	1000000							

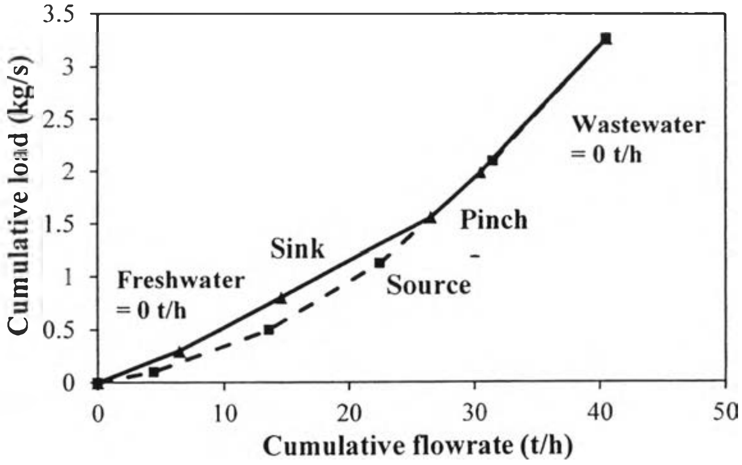

Figure 4.6 Water composite curves for case study 1.2.

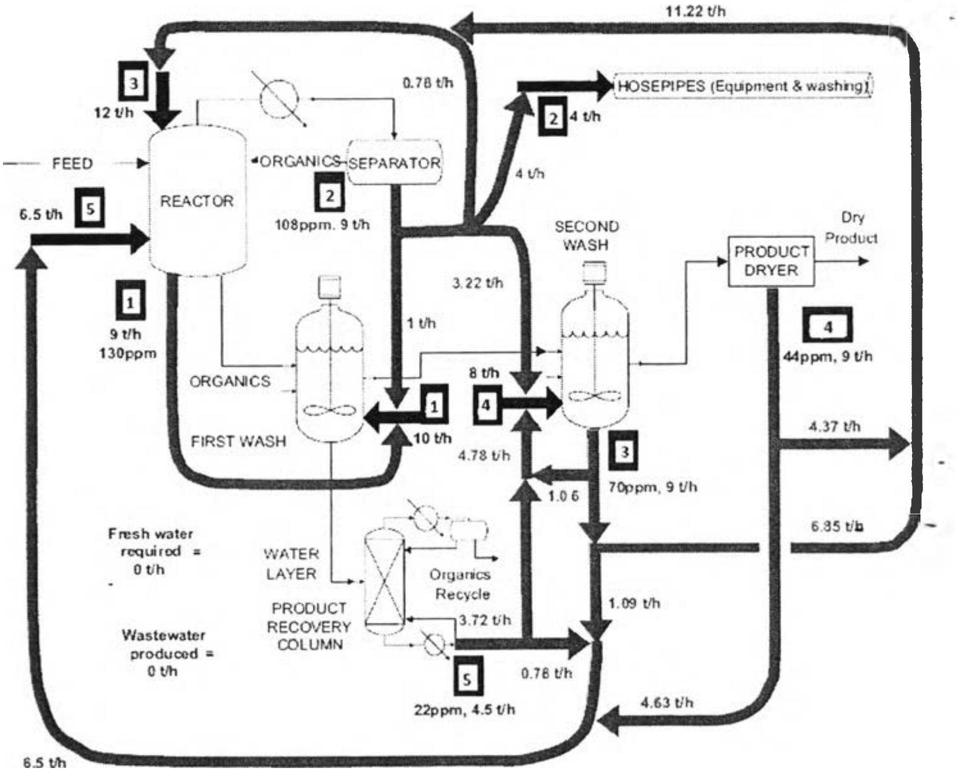

Figure 4.7 Water reuse/recycle network by NNA method (Foo, 2008).

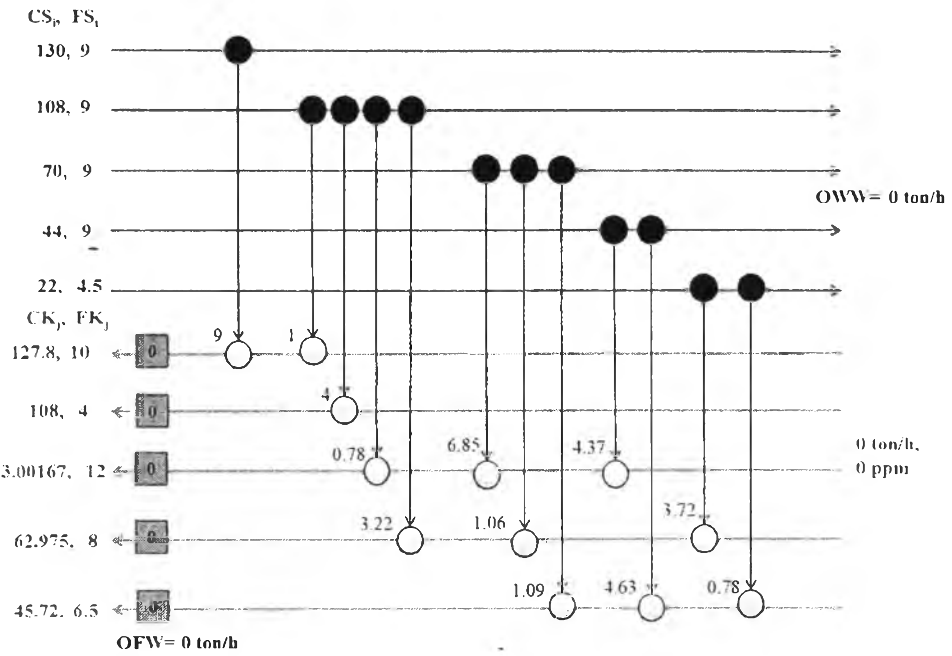

Figure 4.8 Water reuse/recycle network by NNA method in grid diagram (Foo, 2008).

After applied the MILP mathematical model (Eq. 3.1-3.12) by GAMS, the result is according to WCA and WCC that there are zero freshwater input and zero wastewater discharge. In addition, the mass transfer from sources (i) to sinks (j) generated as transfer flowrate shown in Table 4.7 that outcome is water reuse/recycle network shown in Fig. 4.9 represented in grid diagram. Sources which have higher concentration level will transfer contaminant at appropriated splitting flowrate to minimize the amount of freshwater usage to zero. GAMS code is shown in appendix A-5 and the result from GAMS is shown in appendix B-5. The optimal water network has 11 streams split from source to sink that is lower than original network which has 12 streams (Fig. 4.8) because of objective function of MILP model that include minimizing of matching flowrate between source and sink.

Table 4.7 Transfer flow rate, $F_{i,j}$ (t/h) from source (i) to sink (j)

Sink, j / Source, i	1	2	3	4	5
1	9	-	-	-	-
2	1	4	-	3.683	0.317
3	-	-	8.770	0.230	-
4	-	-	3.230	-	5.770
5	-	-	-	4.087	0.413

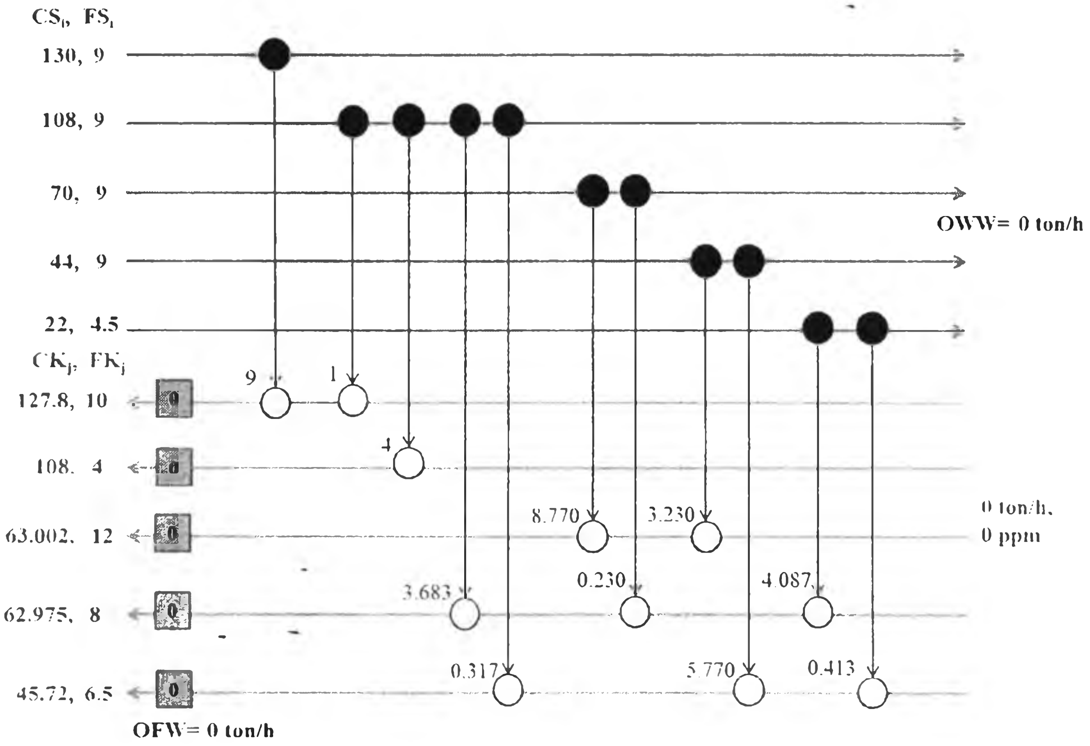

Figure 4.9 Water network of case study 1.2 by GAMS.

4.1.6 <u>Case study 1.3 : Applied Fixed-flowrate problem (Foo, 2008)</u>

This case is adapted from case study 1.2 (Foo, 2008) by change the sinks concentration (CK_j) to lower value for more realistic. Most of parameters still are the same, except sinks concentration that is changed to 20 ppm which lowers than original values shown in Table 4.8. First, WCA and WCC are used to identify the minimum freshwater flowrate shown in Table 4.9 and Fig. 4.10. This case consumes 20.5 t/h of freshwater and generates wastewater at the same value.

Table 4.8 Case study 1.3 data

j	**Water sinks**	**Flowrate, FK_j**	**Concentration, CK_j**	**i**	**Water sources**	**Flowrate, FS_i**	**Concentration, CS_i**
		(t/h)	**(ppm)**			**(t/h)**	**(ppm)**
1	**First wash**	10	20	1	**Reactor discharge**	9	130
2	**Hosepipes**	4	20	2	**Separator**	9	108
3	**Reactor**	12	20	3	**Second wash**	9	70
4	**Second wash**	8	20	4	**Dryer**	9	44
5	**Stream**	6.5	20	5	**Column bottom**	4.5	22

Table 4.9 Water cascade table of case study 1.3

k	**C_k**	**F_j**	**F_i**	**F_i-F_j**	**FC_k**	**Δm_k**	**Cum.Δm_k**	**FW_k**
					22.5			
1	0			0				
					22.5	450		
2	20	40.5		-40.5			450	22.500
					-18	-36		
3	22		4.5	4.5			414	18.818
					-13.5	-297		
4	44		9	9			117	2.659
					-4.5	-117		
5	70		9	9			0	**0**
					4.5	171		
6	108		9	9			171	1.583
					13.5	297		
7	130		9	9			468	3.6
					22.5			

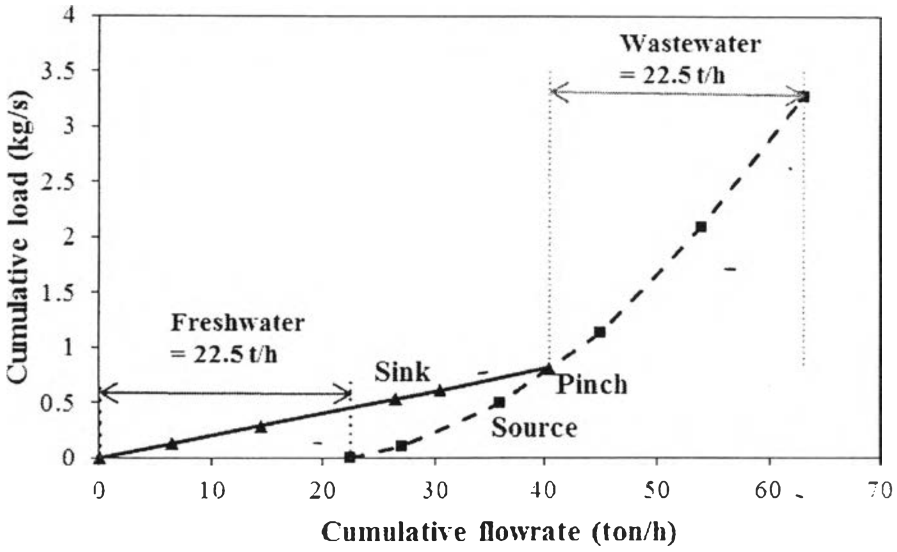

Figure 4.10 Water composite curves for case study 1.3.

Next, MILP mathematical model (Eq. 3.1-3.12) is applied by GAMS. It consumes 22.5 t/h of freshwater and generates 22.5 t/h of wastewater. Amount of freshwater used at each sink (FW_j), concentration of sink (CK_j) and wastewater generate of source (WW_i) are shown in Table 4.10 and transfer flowrate ($F_{i,j}$) from source (i) to sink (j) is shown in Table 4.11.Water network for this case is shown in Fig. 4.11 as grid diagrams. GAMS code for this case is shown in appendix A-6 and the result from GAMS is shown in appendix B-6.

Table 4.10 Minimum freshwater and wastewater of case study 1.3 by GAMS

Sink, j	**1**	**2**	**3**	**4**	**5**	**OFW**
FW_j (t/h)	5.826	0.364	6.545	5.714	4.051	**22.5**
CK_j (ppm)	20	20	20	20	20	
Source, i	**1**	**2**	**3**	**4**	**5**	**OWW**
WW_i (t/h)	9	9	4.5	0	0	**22.5**

Table 4.11 Transfer flow rate, $F_{i,j}$ (t/h) from source to sink of case study 1.3 by GAMS

Sink,j / Source, i	1	2	3	4	5
1	-	-	-	-	-
2	-	-	-	-	-
3	0.629	-	-	2.286	1.586
4	3.545	-	5.455	-	-
5	-	3.636	-	-	0.864

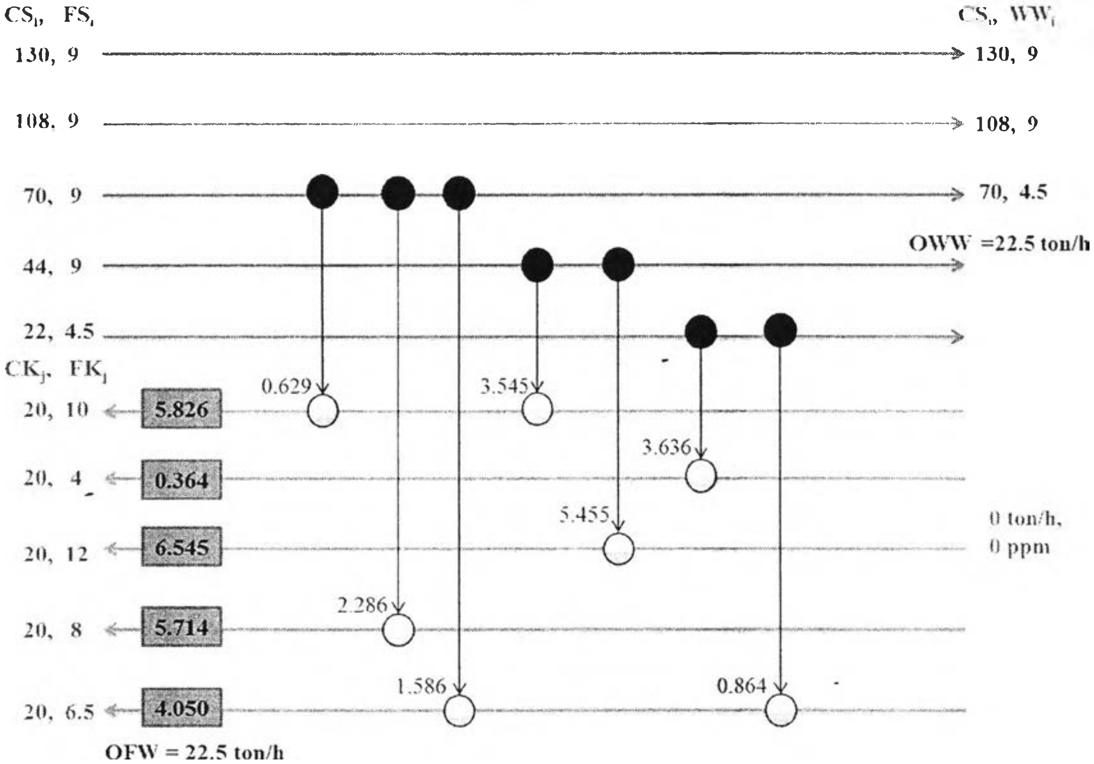

Figure 4.11 Water network of case study 1.3 by GAMS

4.2 Water Network Design with Regeneration Unit

Case study 2 is paper mills process (Tan *et al.*, 2007) described before in background and literature review section shown in Fig. 4.12 and Fig. 4.13 for grid diagram. Sinks and sources stream data are shown in Table 4.12. This existing process has six sinks and four sources, consumes 1989.06 t/h of freshwater with operating cost of 0.043 $/t for treat freshwater before use and discharges 1680.3 t/h of wastewater with treatment cost of 0.295 $/t to satisfy the river contaminant limitation. Pinch analysis was used to retrofit the water network of this process by design more complex network and add regeneration unit. Economics data of regeneration unit shown in Table 4.13 is used to determine the most cost effective water network with regeneration units. Dissolve air floatation (DAF) which is physical treatment equipment that removes suspended solids (TSS) from wastewater by bubble air is used for regenerate wastewater.

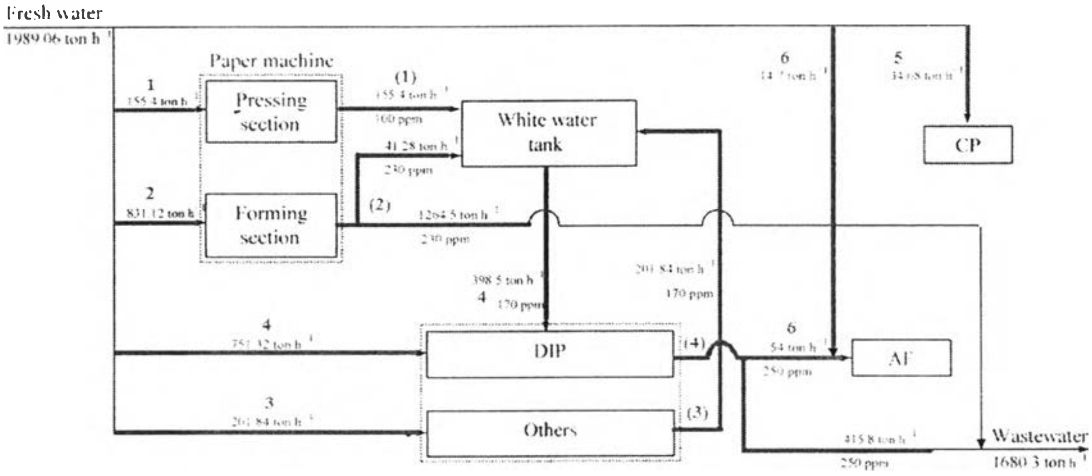

Figure 4.12 Paper mills existing process case study 2 (Tan *et al.*, 2007).

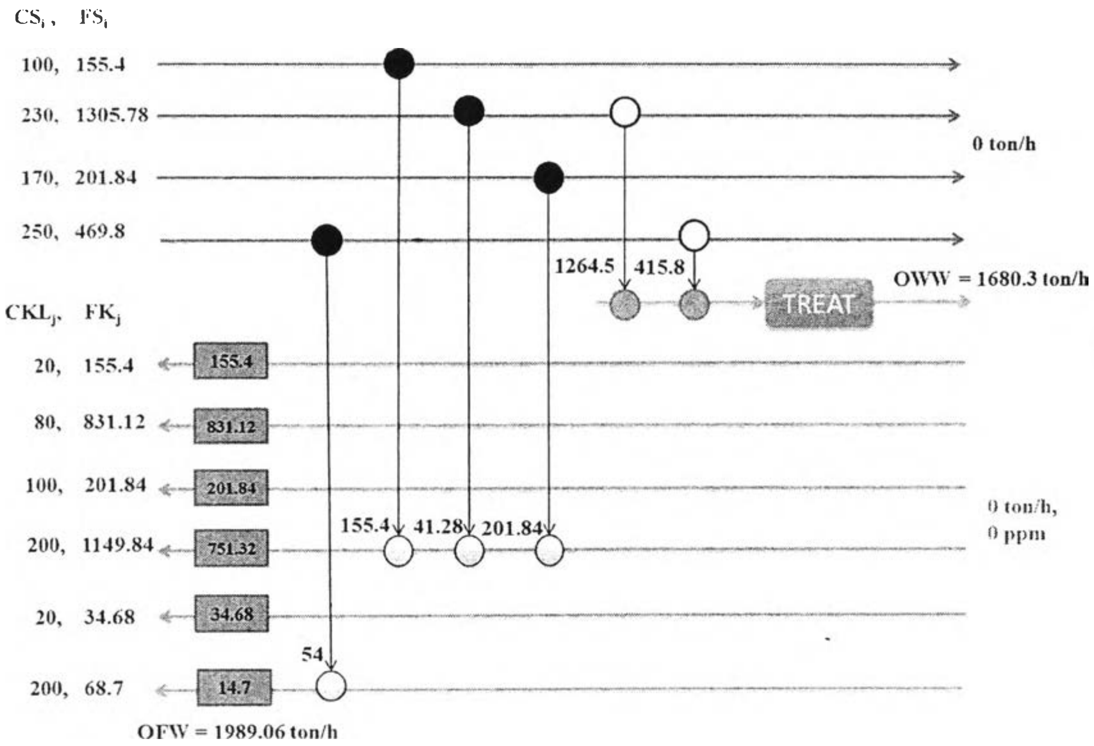

Figure 4.13 Paper mills exists process case study 2 on grid diagram.

Table 4.12 Sinks and sources data for case study 2 (Tan *et al.*, 2007)

j	Sinks	Flowrate, FK$_i$	Concentration, CK$_i$	i	Sources	Flowrate, FS$_i$	Concentration, CS$_i$
		(t/h)	(ppm)			(t/h)	(ppm)
1	**Pressing**	155.4	20	1	**Pressing**	155.4	100
2	**Forming**	831.12	80	2	**Forming**	1305.78	230
3	**Others**	201.84	100	3	**Others**	201.84	170
4	**DIP**	1149.84	200	4	**DIP**	469.8	250
5	**CP**	34.68	20				
6	**AF**	68.7	200				

Table 4.13 Economics data for regeneration unit (Tan *et al.*, 2007)

Regeneration unit **DissolveAir Floatation (DAF)**	
CR (ppm)	30
Hydraulic loading rate (ton/m^{2}h)	1.807
Operating cost ($/t)	0.15
Costing equation per unit ($)	2310.6 (Area)+780876
Piping estimation fraction	0.16

First, the minimum freshwater usage before retrofitting by regeneration is found by water cascade analysis and water composite curve shown in Table 4.14 and Fig. 4.14 accounting for 848.12 t/h and generates 539.36 t/h of wastewater. Both methods can found the minimum freshwater and wastewater flowrate without concerning some of matching from source to sink in existing network (Fig. 4.13). After applied with NLP mathematical program, real potential to save freshwater is found in regard to the matching of existing network. The result is 852.816 t/h of freshwater is required and 544.057 t/h of wastewater is discharged. Amount of freshwater used at each sink (FW_j), concentration of sink (CK_j) and wastewater generate of source (WW_i) are shown in Table 4.15 and transfer flowrate ($F_{i,j}$) from source (i) to sink (j) is shown in Table 4.16. The optimal water network for this case is shown in Fig. 4.15. GAMS code for this case before retrofitting is shown in appendix A-7 and the result from GAMS is shown in appendix B-7.

The way to improve is adding the DAF units for treat the wastewater at the proper amount of regeneration flowrate. From previous study (Tan *et al.*, 2007), the maximum regeneration flowrate (FR_{max}) is sought by plot the freshwater flowrate versus regeneration flowrate. The result shown in Fig. 4.16, maximum regeneration flowrate is 620.265 t/h imply that at this point of FR_{max}, the regenerated water cannot be further reused since the water network had reached its limitation in terms of reusing/recycling of the regenerated.

Table 4.14 Water cascade table before retrofitting for case study 2

k	C_k	F_j	F_i	F_i-F_j	FC_k	Δm_k	Cum.Δm_k	FW_k
					848.1209			
1	0			0				
					848.120	16962.417		
2	20	190.08		-190.08			16962.417	848.120
					658.040	39482.452		
3	80	831.12		-831.12			56444.87	705.560
					-173.079	-3461.5826		
4	100	201.84	155.4	-46.44			52983.287	529.832
					-219.519	-15366.339		
5	170		201.84	201.84			37616.948	221.276
					-17.679	-530.37391		
6	200	1218.54		-1218.54			37086.574	185.432
					-1236.21	-37086.574		
7	230		1305.78	1305.78			0	**0**
					69.560	1391.2174		
8	250		469.8	469.8			1391.2174	5.56486
					539.3609	539226029		
9	1000000			0			539227421	539.227

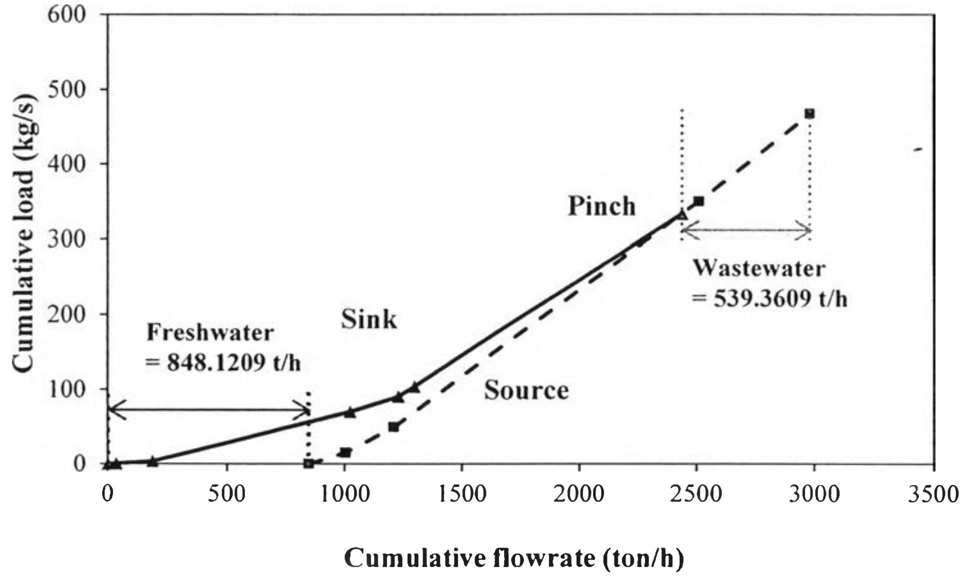

Figure 4.14 Water composite curves before retrofitting for case study 2.

Table 4.15 Minimum freshwater and wastewater of case study 2 before retrofitting by GAMS

Sink, j	**j1**	**j2**	**j3**	**j4**	**j5**	**j6**	**OFW**
FW_j (t/h)	141.887	542.035	114.083	9.49	31.664	13.657	**852.816**
CK_j (ppm)	20	80	100	200	20	200	
Source, i	**i1**	**i2**	**i3**	**i4**			**OWW**
WW_i (t/h)	0	128.257	0	415.8			**544.057**

Table 4.16 Transfer flow rate, $F_{i,j}$ (t/h) from source to sink of case study 2 before retrofitting by GAMS

Sink,j **Source, i**	**1**	**2**	**3**	**4**	**5**	**6**
1	-	-	-	155.4	-	-
2	13.513	289.085	87.757	783.11	3.016	1.043
3	-	-	-	201.84	-	-
4	-	-	-	-	-	54

Retrofit minimum freshwater is identified by recalculate with maximum regeneration flow in water cascading which shown in Table 4.17. Amount of freshwater can be reduced to 308.76 t/h. And there discharge no waste because of 620.265 t/h of waste is regenerated and reuse that be added on row 3 at 30 ppm.

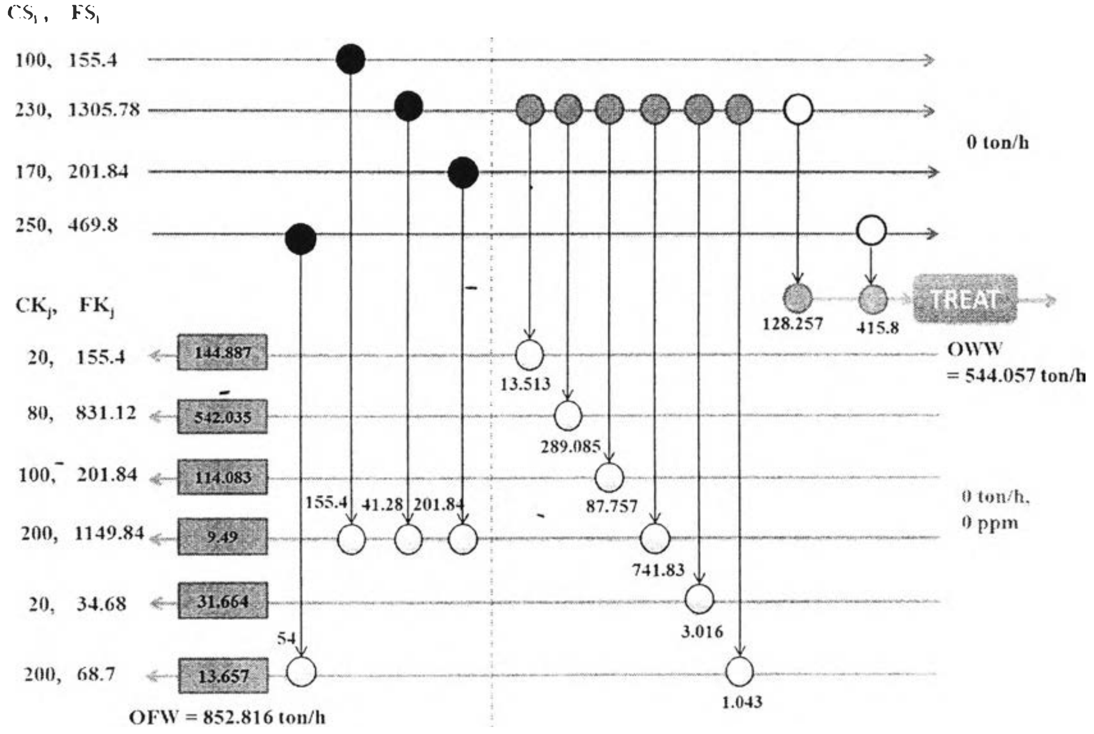

Figure 4.15 Water network of study 2 by GAMS.

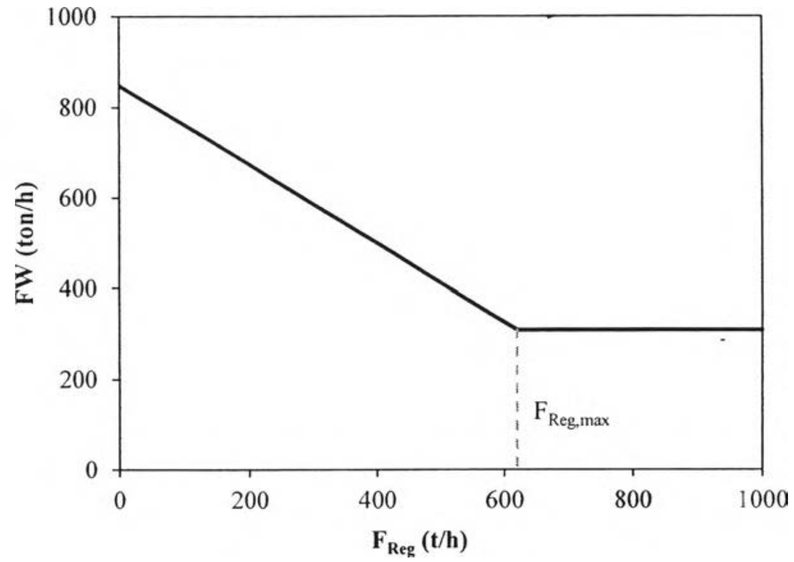

Figure 4.16 Freshwater versus regeneration (Tan *et al.*, 2007).

Table 4.17 Water cascade table after regenerate with 620.265 t/h

k	C_k	F_j	F_i	F_i-F_j	FC_k	Δm_k	Cum.Δm_k	FW_k
					308.76			
1	0			0				
					308.76	6175.2		
2	20	190.08		-190.08			6175.2	308.76
					118.68	1186.8		
3	**30**		**620.265**	620.265			7362	245.4
					738.945	36947.25		
4	80	831.12		-831.12			44309.25	553.8656
					-92.175	-1843.5		
5	100	201.84	155.4	-46.44			42465.75	424.6575
					-138.615	-9703.05		
6	170		201.84	201.84			32762.7	192.7218
					63.225	1896.75		
7	200	1218.54		-1218.54			34659.45	173.2973
					-1155.32	-34659.45		
8	230		1305.78	1305.78			0	**0**
					150.465	3009.3		
9	250		469.8	469.8			3009.3	12.0372
					620.265	620109934		
10	1000000			0			620112943	620.1129

Retrofit water network by pinch analysis (Tan *et al.*, 2007) is shown in Fig. 4.17. Next, the water network with regeneration unit which is generated by NLP mathematical model by Eq. 3.26-3.43 where objective is to maximize cost saving is shown in Fig. 4.18. Three splitting flowrate are the same as existing network except 54 t/h from source four to sink six on the left part of dash line. More eight splitters are added to network before and after regeneration on the right part of dash line. Freshwater and wastewater are reduced compare with pinch analysis. Amount freshwater achieve the minimum value which is 308.76 t/h, all wastewater is recycle by regeneration unit and no waste discharge to treatment. Table 4.18 shows the comparison of results and economic values between pinch analysis and mathematical model. GAMS code for this case with regeneration is shown in appendix A-8 and the result from GAMS is shown in appendix B-8.

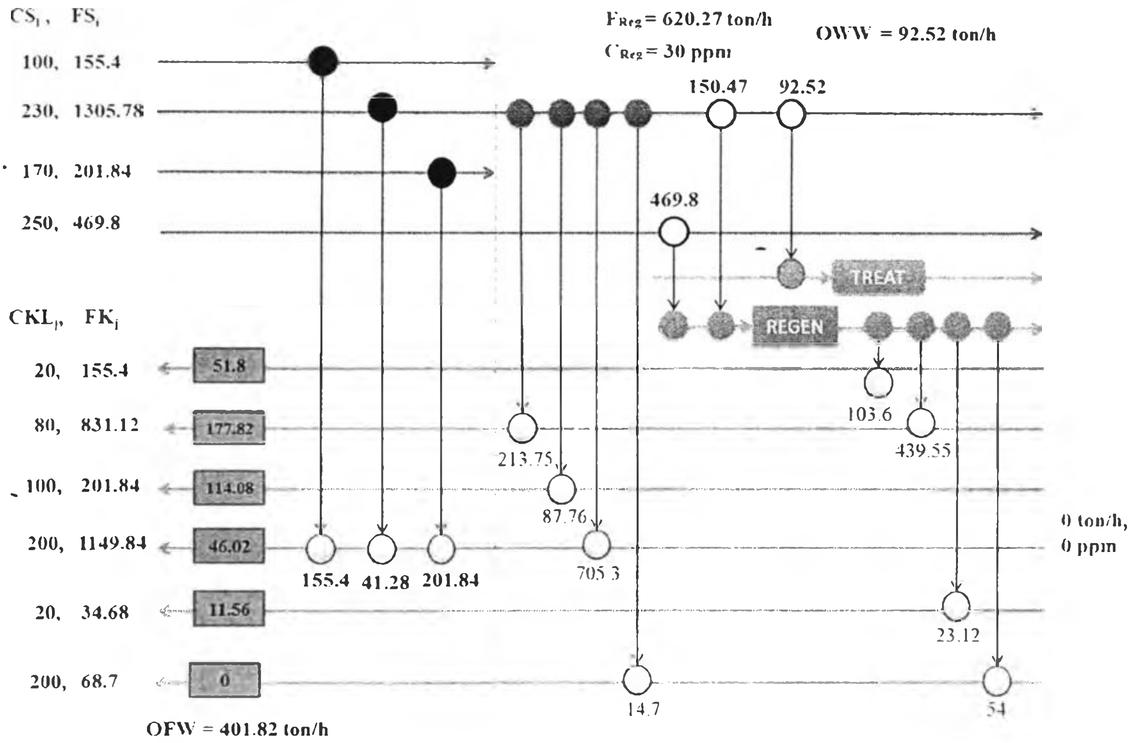

Figure 4.17 Retrofit water network of case study 2 by pinch analysis in grid diagram (Tan *et al.*, 2007).

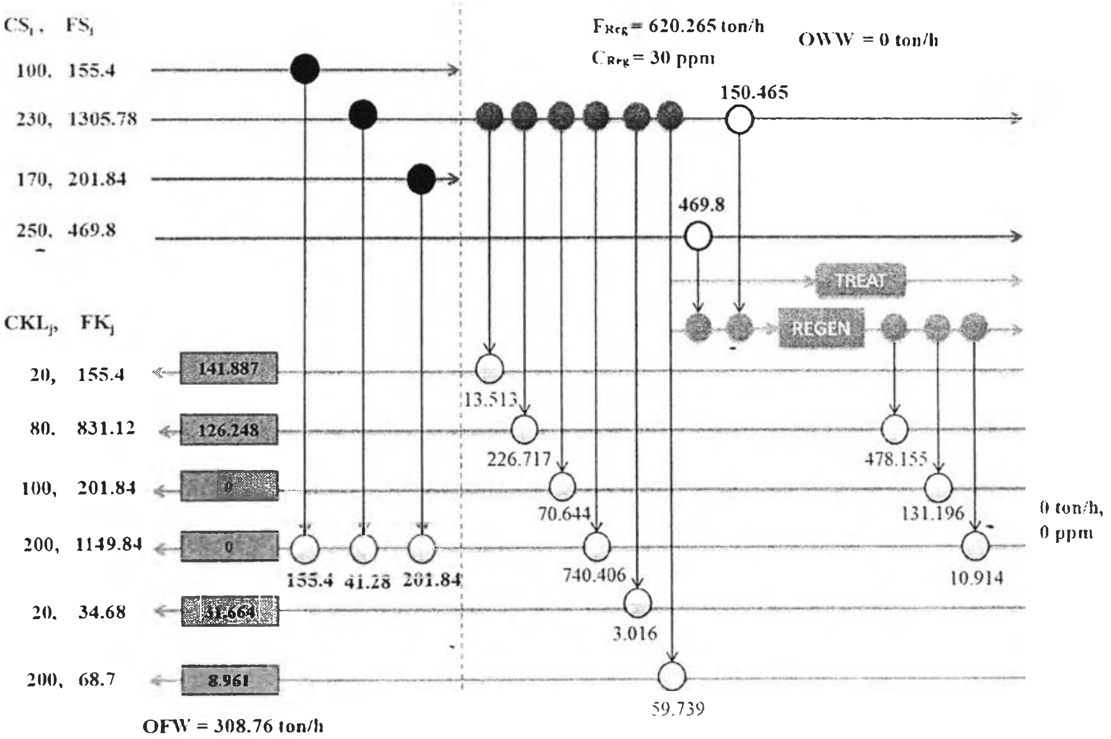

Figure 4.18 Retrofit water networks of case study 2 by NLP (GAMS) in grid diagram.

Table 4.18 Economics result comparison

Results	Existing WN	Retrofit WN	
		Pinch (Tan *et al.,2007*)	NLP (GAMS)
Overall freshwater (t/h)	1989.06	401.28	308.76
Overall wastewater (t/h)	1680.3	92.52	0
Regeneration flowate (t/h)	0	620.27	620.265
Number of splitting	4	12	12
Investment cost ($)	0	3,909,985.30	3,909,942.45
Operating cost ($/y)	4,138,829.23	975,439.78	752,720.32
Saving ($/y)	0	3,163,389.45	3,386,108.91
Payback period (y)	-	1.236	1.155

4.3 Water Network Design with Several Treating Units

4.3.1 Case study 3.1 : Two treatingt units and non-fixed piping cost

Case study 3.1 consist of two process sources and two process sinks with known flowrate and composition which shown in Table 4.19. Waste composition limit is 0.015. Treatment unit data are shown in Table 4.20 that have two units with difference efficiency and cost data and piping cost data are shown in Table 4.21. There have two sources of freshwater which composition are 0 and 0.005 that cost are $1.9\text{x}10^{-3}$ \$/kg and $1.4\text{x}10^{-3}$ \$/kg respectively. The minimum flowrate is 300 kg/h. The proposed model was implemented in GAMS. The parameter HY and KY were fixed as 8000 h/y and 0.333 year^{-1}, respectively. The optimal solution is carried out by cascading four-step calculation procedure. First LP solver is run for initialization to the next solver. Second solver is run by initializing some variable in order to make all display flowrate over 300 kg/h. And the proper treatment unit and stage is chosen from this step. For the third calculation, all variables which found from previous step are set as parameter in order to get piping cost and total annual cost (TAC). Then, all variable are re-calculated to find the most optimal solution by changing of some flowrate to satisfy the most economical pining cost. The results from each step calculation are shown in Table 4.22 where the minimal TAC is 39,331.12 \$/y. The optimal water network is shown in Fig. 4.19 and the result comparison are shown in Table 4.23 that approximately be similar to literature results (Sieniutycz *et al.*, 2009). GAMS code for this case is shown in appendix A-9 and the result from GAMS is shown in appendix B-9.

Table 4.19 Sources and sinks data for case study 3.1 (Sotelo-Pichardo *et al.*, 2011)

Source i	Flowrate, FSi (kg/h)	Composition, CSi	**Sink j**	Flowrate, FKj (kg/h)	Composition, CKLj
1	2500	0.035	**1**	2800	0.014
2	2870	0.024	**2**	2300	0.012
			Waste	Flowrate	Composition limit, CWL
			1	-	0.014

Table 4.20 Treatment unit data for case study 3.1 (Sotelo-Pichardo *et al.*, 2011)

Treatment unit	**Unit1**	**Unit2**
Efficiency factor	0.91	0.72
0≤ Flowrate ≤1790		
Installation fixed cost ($)	9875.43	7822.52
Installation variable cost ($/kg)	8.58269	7.14466
1791≤ Flowrate ≤3580		
Installation fixed cost ($)	13852.9	11133.56
Installation variable cost ($/kg)	6.36064	5.29491
3580≤ Flowrate ≤5370		
Installation fixed cost ($)	16125.94	13025.75
Installation variable cost ($/kg)	5.72571	4.76637
Unitary operation cost ($/kg)	0.79x10^{-3}	0.63x10^{-3}
Capacity increasing fixed cost ($)	800	900
Capacity increasing variable cost ($/kg)	1.1367	0.9548

Table 4.21 Piping cost data for case study 3.1 (Sotelo-Pichardo *et al.*, 2011)

i,j	**CPF1 (\$/y)**	**CP1 x 10^{-4} (\$/kg)**
1,1	1.1	1.1
1,2	1.3	1.2
2,1	0.8	0.8
2,2	1.4	1.3
i,u	**CPF2 (\$/y)**	**CP2 x 10^{-4} (\$/kg)**
1,1	1.2	1.2
1,2	1.4	1.1
2,1	1.1	0.9
2,2	1.5	1
u,w	**CPF3 (\$/y)**	**CP3 x 10^{-4} (\$/kg)**
1,2	0.4	0.5
2,1	0.6	0.4
w,j	**CPF4 (\$/y)**	**CP4 x 10^{-4} (\$/kg)**
1,1	1.4	1.3
1,2	1.3	1.1
2,1	1.2	1.1
2,2	1	0.8
r,j	**CPF5 (\$/y)**	**CP5 x 10^{-4} (\$/kg)**
1,1	1.4	1.6
1,2	1.7	1.7
1,3	1.3	1.4
1,4	1.9	1.5
i	**CPF6 (\$/y)**	**CP6 x 10^{-4} (\$/kg)**
1	0.6	0.7
2	1.3	1.4
w	**CPF7 (\$/y)**	**CP7 x 10^{-4} (\$/kg)**
1	1.1	0.2
2	0.9	0.2

Table 4.22 Result of case study 3.1 by four-step calculation

Result	Calculation 1	Calculation 2	Calculation 3	Calculation 4
$FW_{r,j}$ (kg/h)	$FW_{2,1} = 1473.684$ $FW_{2,2} = 1452.632$	$FW_{1,2} = 405.417$	$FW_{1,2} = 405.417$	$FW_{1,1} = 405.417$
$xF_{i,j}$ (kg/h)	$xF_{2,1} = 1326.316$ $xF_{2,2} = 847.368$	$xF_{2,1} = 1457.074$ $xF_{2,2} = 1037.509$	$xF_{2,1} = 1457.074$ $xF_{2,2} = 1037.509$	$xF_{2,1} = 1518.324$ $xF_{2,2} = 976.259$
$yF_{i,u}$ (kg/h)	-	$yF_{1,1} = 2500$	$yF_{1,1} = 2500$	$yF_{1,1} = 2500$
$tF_{w,u}$ (kg/h)	-	-	-	-
$zF_{w,j}$ (kg/h)	-	$zF_{1,1} = 1342.926$ $zF_{1,2} = 857.074$	$zF_{1,1} = 1342.926$ $zF_{1,2} = 857.074$	$zF_{1,1} = 876.259$ $zF_{1,2} = 1323.741$
$WW1_i$ (kg/h)	-	$WW1_2 = 375.417$	$WW1_2 = 375.417$	$WW1_2 = 375.417$
$WW2_w$ (kg/h)	-	$WW2_1 = 300.000$	$WW2_1 = 300.000$	$WW2_1 = 300.000$
FTI_u (kg/h)	-	$FTI_1 = 2500$	$FTI_1 = 2500$	$FTI_1 = 2500$
Waste Composition	-	0.0147	0.0147	0.0147
Freshwater Cost ($/y)	32,774.74	6,162.33	6,162.33	6,162.33
Treatment Cost ($/y)	-	9,908.25	9,908.25	9,908.25
Operation Cost ($/y)	-	15,800	15,800	15,800
Piping Cost ($/y)	-	-	7,592.44	7,460.54
Total Annual Cost ($/y)	-	-	**39,463.02**	**39,331.12**

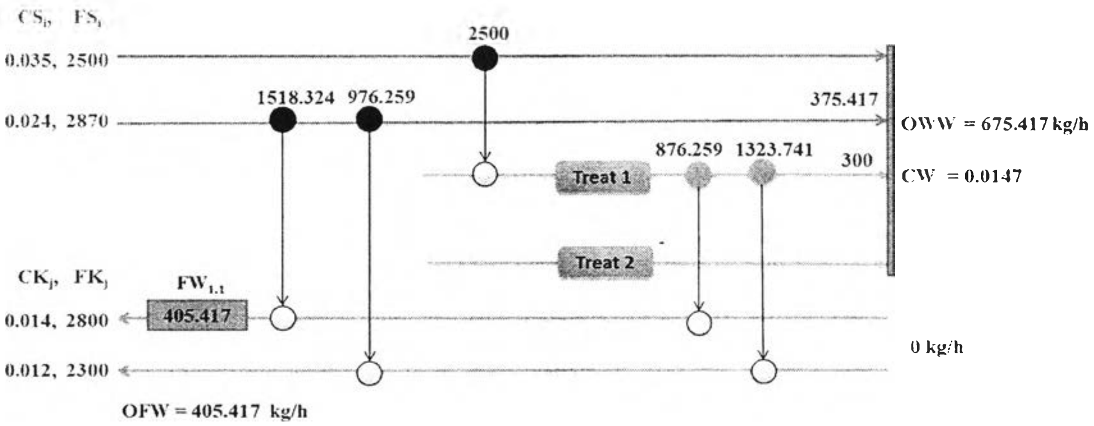

Figure 4.19 Optimal water network of case study 3.1 in grid diagram.

Table 4.23 Result comparison of case study 3.1

Result	Sotelo *et al.*, 2011	Four-step calculation
Waste composition	0.015	0.0147
Freshwater flowrate (kg/h)	405.42	405.417
Waste flowrate (kg/h)	675.42	675.417
Freshwater cost ($/y)	6162.384	6162.333
Treatment capital cost ($/y)	9908.248	9908.248
Treatment operation cost ($/y)	15800	15800
Piping cost ($/y)	7460.544	7,460.54
Total annual cost ($/y)	**39331.176**	**39331.12**

4.3.2 Case study 3.2 : Three treatingt units and fixed piping cost

Case study 3.2 consist of four process sources and two process sinks with known flowrate and concentration which shown in Table 4.24. Waste concentration limit is 5 ppm. Treatment unit data are shown in Table 4.25 that have two units with difference efficiency and cost data and piping cost data are shown in Table 4.26. There have two sources of freshwater which concentration are 0 and 5 ppm that cost are 1.45×10^{-3} $/kg and 0.94×10^{-3} $/kg respectively. The minimum flowrate is 300 kg/h. The proposed model was implemented in GAMS. The parameter HY and KY were fixed as 8000 h/y and 0.333 year^{-1}, respectively. The optimal solution is carried out by cascading four-step calculation procedure. First LP solver is run for initialization to the next solver. Second solver is run by initializing FTI_u variable to get the most economical treatment unit and stage. For the third calculation, all variables which found from previous step are set as parameter in order to get piping cost and total annual cost (TAC). The last calculation show the same solution as previous calculation because of piping cost were fixed that no need to change flowrate and matching. The results from each step calculation are shown in Table 4.27 where the minimal TAC is 957,884.804 $/y. The optimal water network is shown in Fig. 4.21 and the result comparison are shown in Table 4.28 that approximately be similar to literature results (Sieniutycz *et al.*, 2009). GAMS code for this case is shown in appendix A-10 and the result from GAMS is shown in appendix B-10.

Table 4.24 Sources and sinks data for case study 3.2 (Sotelo-Pichardo *et al.*, 2011)

Source i	Flowrate, FSi (kg/h)	Concentration, CSi	**Sink** j	Flowrate, FKj (kg/h)	Concentration, CKLj
1	2880	0	**1**	4320	0
2	18000	14	**2**	20880	10
3	21240	25	**Waste**	Flowrate	Concentration limit, CWL
4	5040	34	**1**	-	5

Table 4.25 Treatment unit data for case study 3.2 (Sotelo-Pichardo *et al.*, 2011)

Treatment unit	**Unit1**	**Unit2**	**Unit3**
Efficiency factor	0.93	0.84	0.76
0≤ Flowrate ≤3187			
Installation fixed cost	12470.71	9134.52	7873.48
Installation variable cost	8.4443	6.5109	6.1027
3187≤ Flowrate ≤6374			
Installation fixed cost	19438.82	14506.78	12908.94
Installation variable cost	6.2581	4.8252	4.5227
6375≤ Flowrate			
Installation fixed cost	23420.05	17576.92	15786.6
Installation variable cost	5.6334	4.3436	4.0713
Unitary operation cost ($/kg)	$0.9\text{x}10^{-3}$	$0.6\text{x}10^{-3}$	$0.5\text{x}10^{-3}$

Table 4.26 Piping cost data for case study 3.2 (Sotelo-Pichardo *et al.*, 2011)

i,j	**CPF1 ($/y)**	**CP1 x 10^{-3} ($/kg)**
	0.82	1.4
i,u	**CPF2 ($/y)**	**CP2 x 10^{-3} ($/kg)**
	0.96	1.2
u,w	**CPF3 ($/y)**	**CP3 x 10^{-3} ($/kg)**
	0.7	0.63
w,j	**CPF4 ($/y)**	**CP4 x 10^{-3} ($/kg)**
	0.89	1.11
r,j	**CPF5 ($/y)**	**CP5 x 10^{-3} ($/kg)**
	1.635	0.67
i	**CPF6 ($/y)**	**CP6 x 10^{-3} ($/kg)**
	0.82	1.4
w	**CPF7 ($/y)**	**CP7 x 10^{-3} ($/kg)**
	0.89	1.11

Table 4.27 Results of case study 3.2 by four-step calculation

Result	Calculation 1	Calculation 2	Calculation 3	Calculation 4
$FW_{r,j}$ (kg/h)	$FW_{1,1}$ = 1440 $FW_{1,2}$ = 5965.714	$FW_{1,1}$ = 1440	$FW_{1,1}$ = 1440	$FW_{1,1}$ = 1440
$xF_{i,j}$ (kg/h)	$xF_{1,1}$ = 2880 $xF_{2,2}$ = 14914.2	$xF_{1,1}$ = 2880 $xF_{2,2}$ = 12485.857	$xF_{1,1}$ = 2880 $xF_{2,2}$ = 12485.857	$xF_{1,1}$ = 2880 $xF_{2,2}$ = 12485.857
$yF_{i,u}$ (kg/h)	-	$yF_{2,2}$ = 3280.408 $yF_{3,2}$ = 21240 $yF_{4,2}$ = 5040	$yF_{2,2}$ = 3280.408 $yF_{3,2}$ = 21240 $yF_{4,2}$ = 5040	$yF_{2,2}$ = 3280.408 $yF_{3,2}$ = 21240 $yF_{4,2}$ = 5040
$tF_{w,u}$ (kg/h)	-	-	-	-
$zF_{w,j}$ (kg/h)	-	$zF_{2,2}$ = 8394.143	$zF_{2,2}$ = 8394.143	$zF_{2,2}$ = 8394.143
$WW1_i$ (kg/h)	-	$WW1_2$ = 2233.735	$WW1_2$ = 2233.735	$WW1_2$ = 2233.735
$WW2_w$ (kg/h)	-	$WW2_1$ = 21166.26	$WW2_1$ = 21166.26	$WW2_1$ = 21166.26
FTI_u (kg/h)	-	FTI_2 = 29560.408	FTI_2 = 29560.408	FTI_2 = 29560.408
Waste Concentration (ppm)	-	5	5	5
Freshwater Cost ($/y)	85,906.286	16,704	16,704	16,704
Treatment Cost ($/y)	-	48,609.844	48,609.844	48,609.844
Operation Cost ($/y)	-	141,889.959	141,889.959	141,889.959
Piping Cost ($/y)	-	-	751,118.926	751,118.926
Total Annual Cost ($/y)	-	-	**958,322.730**	**958,322.730**

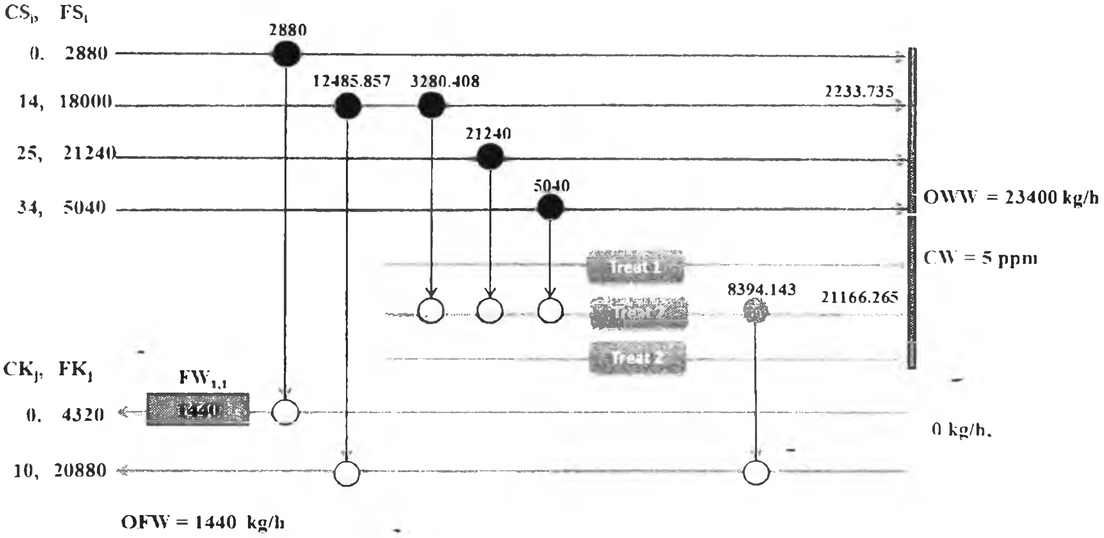

Figure 4.20 Optimal water network of case study 3.2 in grid diagram.

Table 4.28 Result comparison of case study 3.2

Results	Sotelo *et al.*, 2011	Four-step calculation
Waste concentration (ppm)	5	5
Freshwater flowrate (kg/h)	1440	1440
Waste flowrate (kg/h)	23400	23400
Freshwater cost ($/y)	16,704	16,704
Treatment capital cost ($/y)	48,609.85	48,609.84
Treatment operation cost ($/y)	141,889.97	141,889.96
Piping cost ($/y)	751,116.13	751,118.93
Total annual cost ($/y)	**958319.945**	**958,322.729**

4.4 Water-and-Heat-Exchanger Network (WHEN) Design

The case study 4 is adapted from case study 1.3 with defined temperature to illustrate the sequential WHEN model consists of five process sources and five process sinks with known concentration, flowrate and temperature. The example process shown in Fig. 4.22 and defined in Table 4.29. Cost data are shown in Table 4.30. Piping fixed-cost (CPF) and variable cost (CP) of all possible streams are shown in Table 4.31 and Table 4.32. Without WHEN design, the process require 44.5 t/h of freshwater and discharge 44.5 t/h of wastewater. In order to increase sinks temperature to desired values (100 °C) and decrease sources temperature to regulation values (30°C) before discharging, the process consume hot and cold utilities for 3543.75 kW and 4147.5 kW, respectively. Total annual cost of based case is $2,343,023.16 per year.

First of all, without sinks and sources temperature included, minimum freshwater and wastewater are identified by water cascade analysis (WCA) and water composite curve (WCC) where result are same as previous result of case study 1.3 as shown in Table 4.9 and Fig. 4.10. The process minimally consume 22.5 t/h of freshwater and discharge 22.5 t/h of wastewater.

Five scenarios of network are studied conssist of based case, optimal network by WN without HEN, optimal network by HEN without WN, optimal WHEN by two-step design, and optimal WHEN by four-step design.

Table 4.29 Sources and sinks data for case study 4

Source i	FS_i (t/h)	CS_i (ppm)	TS_i (°C)	Sink j	FK_j (t/h)	CK_j (ppm)	TK_j (°C)
1	9	130	120	1	10	20	100
2	9	108	100	2	4	20	100
3	9	70	130	3	12	20	100
4	9	44	140	4	8	20	100
5	4.5	22	80	5	6.5	20	100

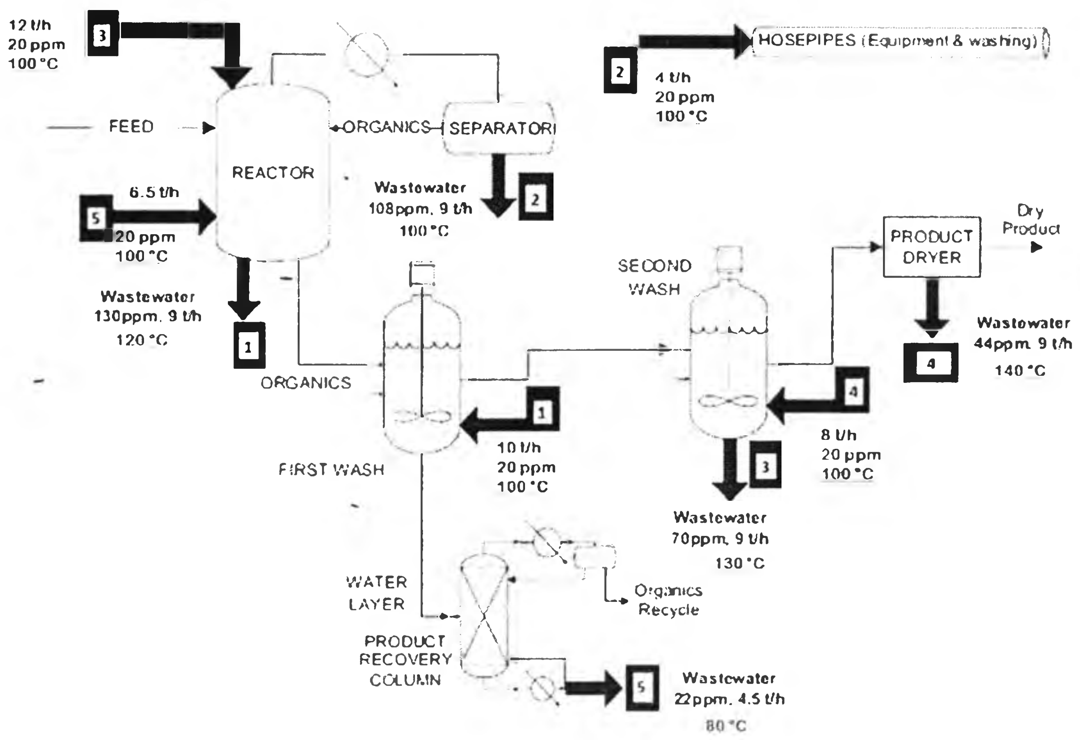

Figure 4.21 Process diagram of case study 4.

Table 4.30 Cost and operating cost parameters

Parameter	Value
Freshwater cost ($/t)	0.375
Cooling utility cost ($/kW· y)	189
Heating utility cost ($/kW· y)	377
Exchangers fixed cost ($)	8000
Exchangers area coefficient cost ($/m^2)	1200
Cost exponent for exchangers	0.6
Overall heat-transfers coefficient (kW/m^2· °C)	0.5
Working hours of plant per year (h)	8000
Annualize factor of investment cost (y^{-1})	0.333
Inlet heating steam temperature (°C)	120
Inlet and outlet cooling water temperature (°C)	10, 20
Freshwater temperature (°C)	25
Wastewater temperature (°C)	30
Exchangers minimum approach temperature (°C)	10

Table 4.31 Piping fixed-cost and variable cost of source to sink streams

Sink j Source i	1		2		3		4		5	
	CPF1 ($/y)	CP1x10^{-3} ($/t)	CPF1 ($/y)	CP1x10^{-3} ($/t)	CPF1 ($/y)	CP1x10^{-3} ($/t)	CPF1 ($/y)	CP1x10^{-3} ($/t)	CPF1 ($/y)	CP1x10^{-3} ($/t)
1	100	1.1	300	1.2	150	1.3	200	1.4	200	1.1
2	200	0.8	250	1.3	100	1.1	220	1.2	150	0.9
3	220	0.9	300	1.3	330	1.1	300	1.4	110	1.1
4	110	1.3	400	1.2	200	1.3	200	1.4	250	1.1
5	200	1.1	300	0.8	100	1.3	300	1.4	250	0.9

Table 4.32 Piping fixed-cost and variable cost of freshwater and wastewater streams

Fresh to Sink j	1		2		3		4		5	
	CPF2 ($/y)	CP2 x10^{-3} ($/t)	CPF2 ($/y)	CP2 x10^{-3} ($/t)	CPF2 ($/y)	CP2 x10^{-3} ($/t)	CPF2 ($/y)	CP2 x10^{-3} ($/t)	CPF2 ($/y)	CP2 x10^{-3} ($/t)
	200	0.7	300	1.4	150	1.2	120	1.1	250	1.3
Source i to Waste	1		2		3		4		5	
	CPF2 ($/y)	CP2 x10^{-3} ($/t)	CPF2 ($/y)	CP2 x10^{-3} ($/t)	CPF2 ($/y)	CP2 x10^{-3} ($/t)	CPF2 ($/y)	CP2 x10^{-3} ($/t)	CPF2 ($/y)	CP2 x10^{-3} ($/t)
	100	0.7	200	1.4	250	1.1	150	1.2	200	1.3

4.4.1 Base case

Without WN and HEN design, the process will consume maximum amout of freshwater and utilities. The process require 44.5 t/h of freshwater and discharge 44.5 t/h of wastewater. In order to increase sinks temperature to desired values (100 °C) and decrease sources temperature to regulation values (30°C) before discharging, the process consume hot and cold utilities for 3543.75 kW and 4147.5 kW, respectively. Total annual cost of based case is $2,343,023.16 per year.

4.4.2 WN design

The optimal WN network is design with minimum freshwater usage to generate WN as shown in Fig. 4.22 with minimal freshwater and piping cost in annual, which are \$67,500 per year and \$3,353.68 per year, respectively. After doing WN, Sinks temperature (TK_1 to TK_5) are rised to 56.67 °C, 75 °C, 77.093 °C, 77.273 °C, and 55 °C, respectively. Flowrate of residue sources i1, i2, and i3 are 9, 9, and 4.5 t/h with the same temperature. Without HEN design, sink and source streams temperature will satisfied by hot and cold utilities, which are 1,496.25 kW of hot utilities and 2,205 kW of cold utilities with eight exhangers as shown in Fig. 4.23 where the total annual cost is \$1,129,537.262 per year. GAMS code for this case is shown in appendix A-11 and the result from GAMS is shown in appendix B-11.

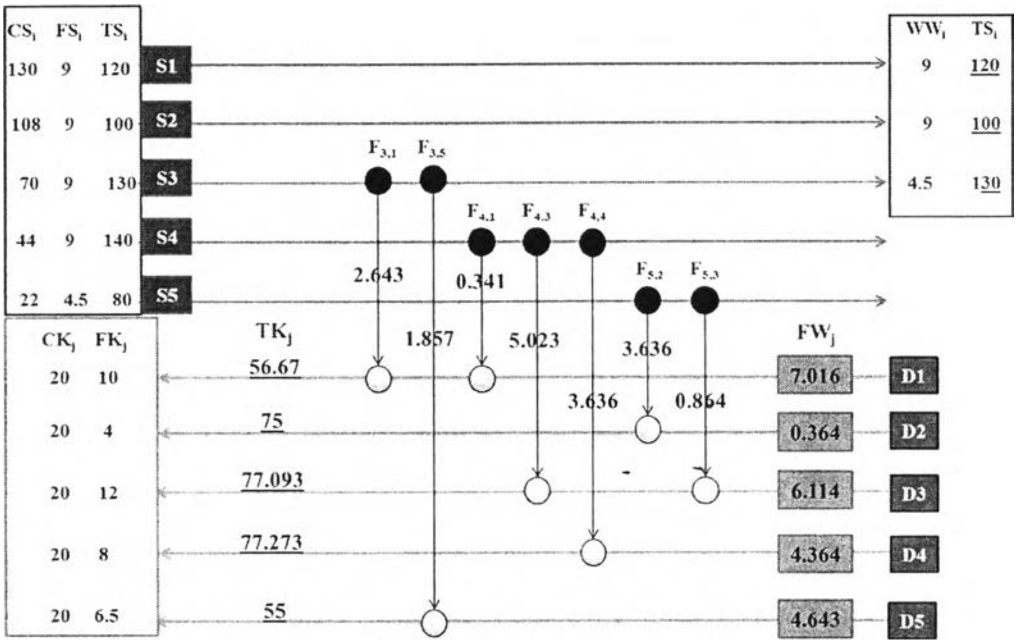

Figure 4.22 WN of case study 4.

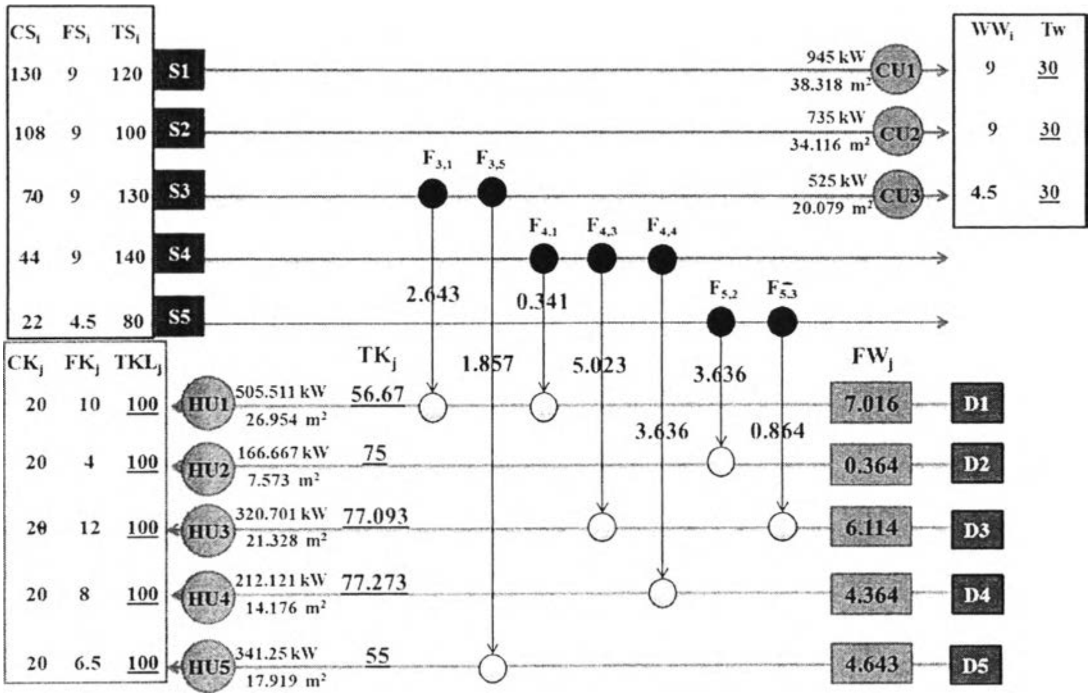

Figure 4.23 Optimal network of case study 4 by WN design.

4.4.1 HEN design

Without optimal WN design, all five sinks is fed by freshwater at required values, which are 10 t/h, 4 t/h, 12 t/h, 10 t/h, and 6.5 t/h with freshwater temperature (25 °C) where the target temperature of sinks is 100 °C. To increase sink temperature to target values, sinks will act like cold streams of HEN. In other words, to decrease source temperature to discharge regulation waste value (30°C), sources will act like hot streams of HEN. Minimum cold utility is 603.75 kW without hot utility consumption as shown in Fig. 4.24. The optimal HEN is shown in Fig. 4.25. GAMS code for this case is shown in appendix A-12 and the result from GAMS is shown in appendix B-12.

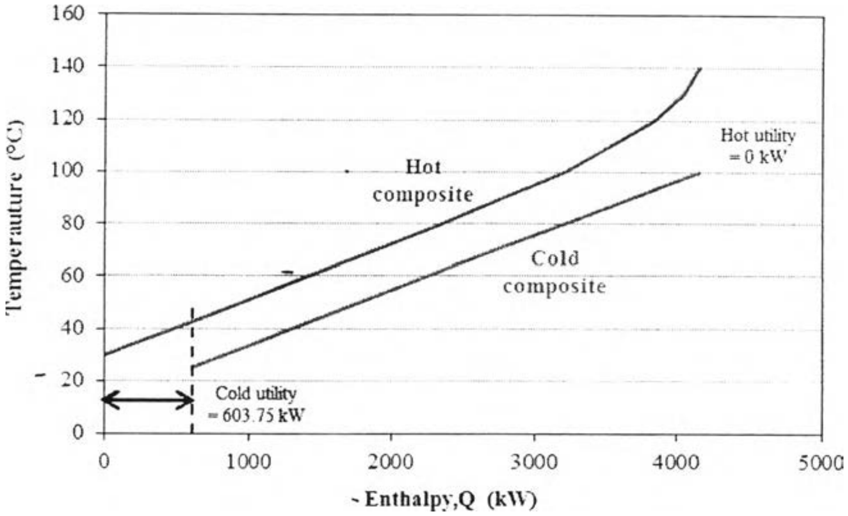

Figure 4.24 Heat composite curve.

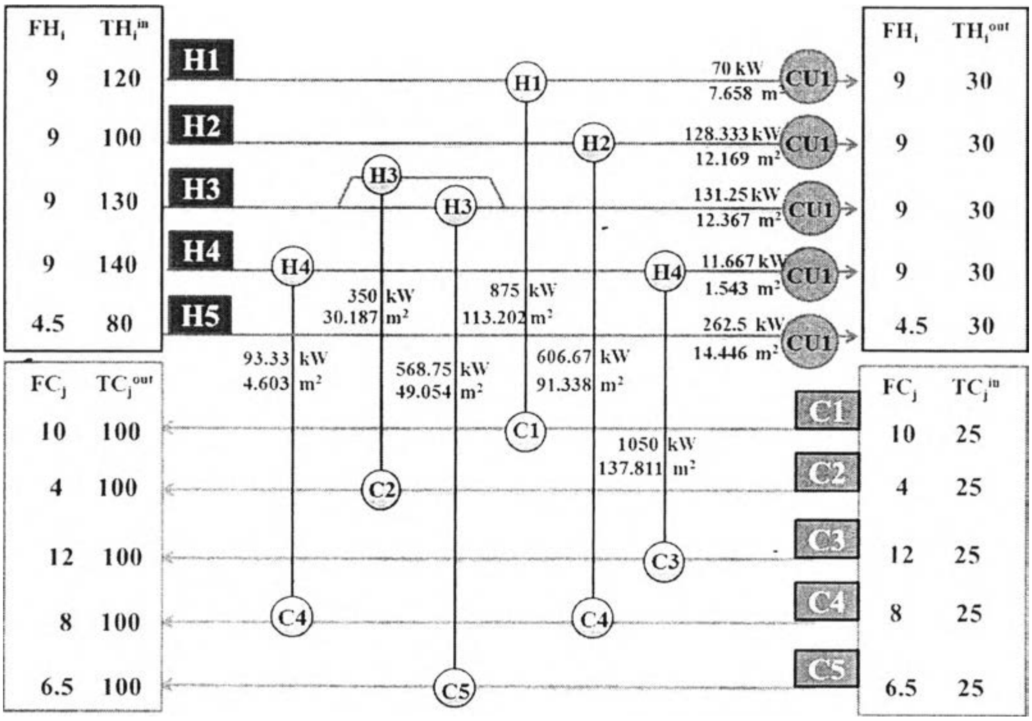

Figure 4.25 Optimal network of case study 4 by HEN design.

4.4.2 WHEN by two-step design

All data are put in the WHEN model (Eq. 3.132-3.178) and calculated by GAMS with two-step approarch calculaion method where the calculation steps are shown in Fig. 3.7, there have two main steps with four solving step.

Step 1 : For first and second solving, minimum freshwater flowrate (FW_j), transfer flowrate ($F_{i,j}$), and minimum waste (WW_i) are found with appropriate make-up streams to complete WN as shown in Fig. 4.22 with minimal freshwater and piping cost in annual, which are \$67,500 per year and \$3,353.68 per year, respectively. After doing WN, Sinks temperature (TK_1 to TK_5) are rised to 56.67 °C, 75 °C, 77.093 °C, 77.273 °C, and 55 °C, respectively. Flowrate of residue sources i1, i2, and i3 are 9, 9, and 4.5 t/h with the same temperature. Before HEN design, minimum hot and cold utilities are preliminary targeted by hot/cold composite curve as shown in Fig. 4.26.

Step 2 : HEN is designed by third and fourth solvings to develop WHEN. The process cosume hot utilities and cold utilities for 268.41 kW and 977.16 kW, respectively with 12 exchanger units. HEN shown in Fig. 4.27 where H1-H3 is hot streams and C1-C5 is cold streams. Total annual cost is \$488,160.624 per year. The optimal WHEN are shown in Fig. 4.28 notice that source streams and sink streams are displayed as S1-S5 and D1-D5, respectively. The overall results are shown in Table 4.33. GAMS code for this case is shown in appendix A-13 and the result from GAMS is shown in appendix B-13.

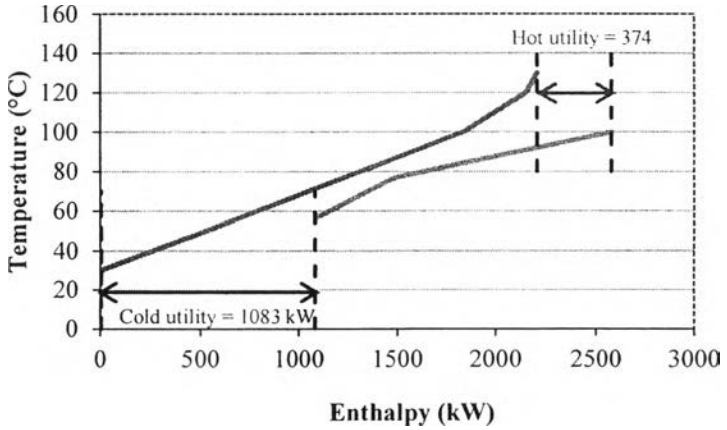

Figure 4.26 Heat composite curve after WN design.

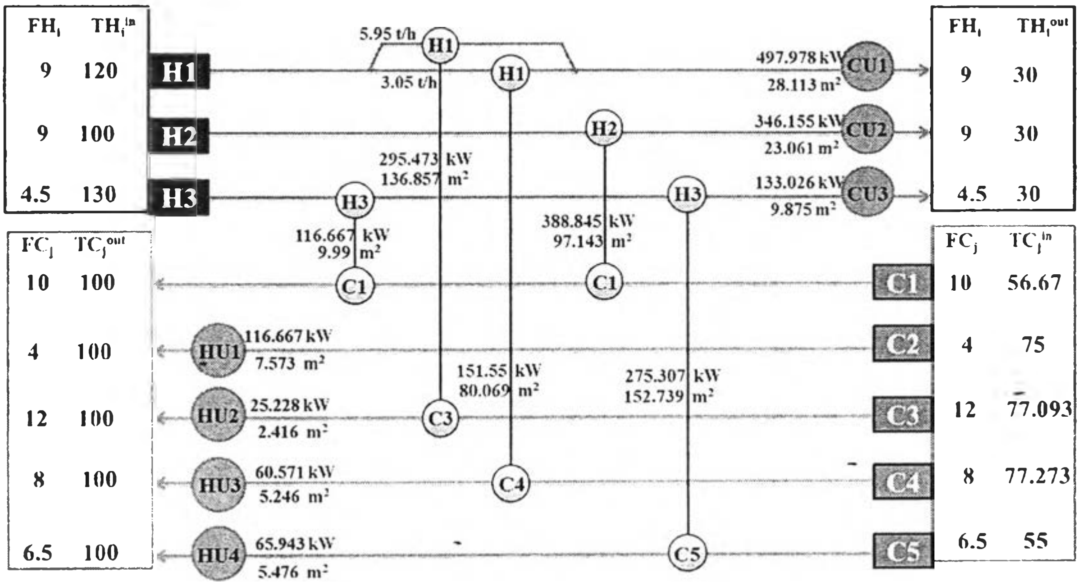

Figure 4.27 HEN of WHEN by two-step design.

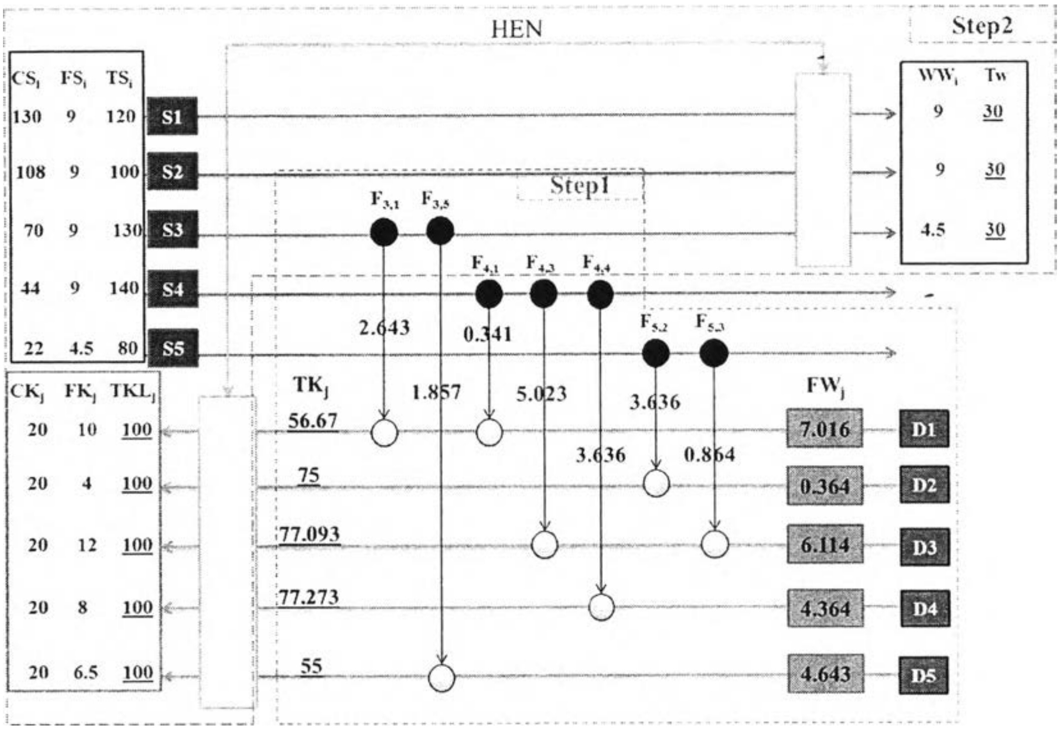

Figure 4.28 Optimal WHEN by two-step design.

4.4.3 WHEN by four-step design

All data are put in the WHEN model as shown in Fig. 3.8 and calculated by GAMS with four-step approarch calculaion method where the calculation steps are shown in Fig. 3.9, there have four main steps with seven solving step.

Step 1 : Overall WN is design where objective is to minimize freshwater and piping cost in annual. The optimal WN is same as two-step design, which are \$67,500 per year and \$3,353.68 per year, respectively. Next, WN are devided into two sections (WN1 and WN2). Transfer flowrate from source to sink ($F_{i,j}$) calculated by first step (see in Fig. 4.22), which has seven streams ($F_{3,1}$, $F_{3,5}$, $F_{4,1}$, $F_{4,3}$, $F_{4,4}$, $F_{5,2}$, and $F_{5,3}$) are separated into WN1 as $F1_{i,j}$ and WN2 as $F2_{i,j}$ by random choosing concerning feasibility of sink temperature in WN2 after step 3. For WN1, there are five streams are chosen consist of $F1_{3,1}$, $F1_{3,5}$, $F1_{4,1}$, $F1_{5,2}$, and $F1_{5,3}$. For WN2, the other two streams are chosen consist of $F2_{4,3}$ and $F2_{4,4}$.

Step 2 : Inlet sink temperature of WN1 ($TOUTC2_j$) are required parameters to calculate WN1 with temperature included and optimal HEN1 but $TOUTC2_j$ have not calculated yet. For continue the calculation process, $TOUTC2_j$ must be assigned by pinch temperature of sink or cold streams, which around 70 °C (see in Fig. 4.26). After WN1 is calculated, sink flowrate and concentration are reached the desired value, sink temperature ($TK1_1$ - $TK1_5$) are rised to 88.224 °C, 79.091 °C, 70.720 °C, 70 °C, and 87.143 °C, respectively, some sources flowrate (S3-S5) are decreased to 4.5 t/h, 8.659 t/h, and 0 t/h, respectively. After that, HEN1 is calculated by residue source streams as hot streams and sink streams as cold streams where the objective is to minimize hot and cold utilities and annualized exchangers cost. HEN1 consume 97.579 kW of hot utility with five exchangers as shown in Fig. 4.29. Source or hot streams temperature ($TOUTH1_1$ - $TOUTH1_4$) are decreased to 84.05 °C, 100 °C, 130 °C, and 85.85 °C, respectively.

Step 3 : WN2 is calculated by transfer flow rate streams ($F2_{i,j}$) where are chosen from step 1, sources inlet flowrate ($FS2_{i,j}$), which are residue source from WN1, and sources inlet temperature (TOUTH1$_i$). Hence, some sinks stream (D2, D3) temperature that are combined by transfer streams and minimum freshwater streams are rised up. Sinks temperature (TK2$_j$) are 25 °C, 52.44 °C, 52.66 °C, 25 °C, and 25 °C, respectively that not over the limit values (TOUTC2$_j$) where are assigned to be 70 °C at step 2.

Step 4 : HEN2 is calculated by residue hot streams from WN1 and WN2 and make-up cold streams by WN2 where the objective is to minimize hot and cold utilities and annualized exchangers cost. Source or hot streams temperature are decreased to waste regulation temperature (30 °C) and sink or cold streams temperature are increased to assigned value (TOUTC2$_j$). HEN2 consume 806.326 kW of cold utilities with eight exchangers as shown in Fig. 4.30. Optimal WHEN designed by step1 through step 4 is shown in Fig. 4.31, there consume 22.5 t/h of freshwater with seven transfer streams, 97.579 kW of hot utility, 806.326 kW of cold utilities with thirteen exchanger units. Total annual cost is \$ 385,981.43 per year. GAMS code for this case is shown in appendix A-14 and the result from GAMS is shown in appendix B-14.

The overall result comparison between base case, WHEN without WN design, WHEN without HEN design, WHEN by two-step design, and four-step are shown in Table 4.33. WHEN by four-step design gives a best result compared with other methods by lowest total annual cost followed by network by HEN design, network by two-step design, and the last network by WN design. Result from four-step design can reduce both freshwater and utilities that is around 83 % save from base case.

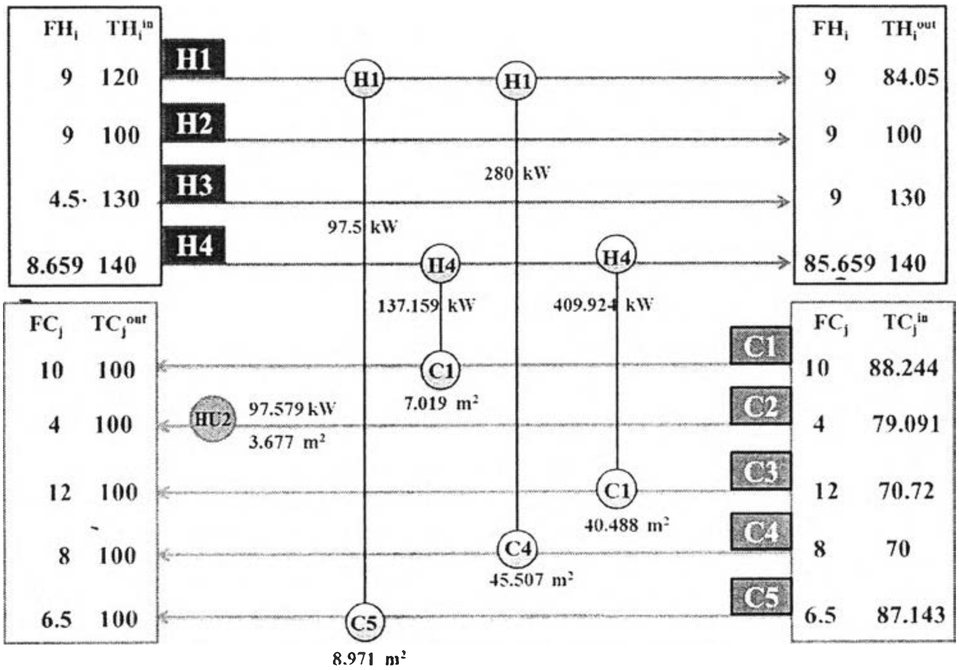

Figure 4.29 HEN in section 1 of WHEN by four-step design.

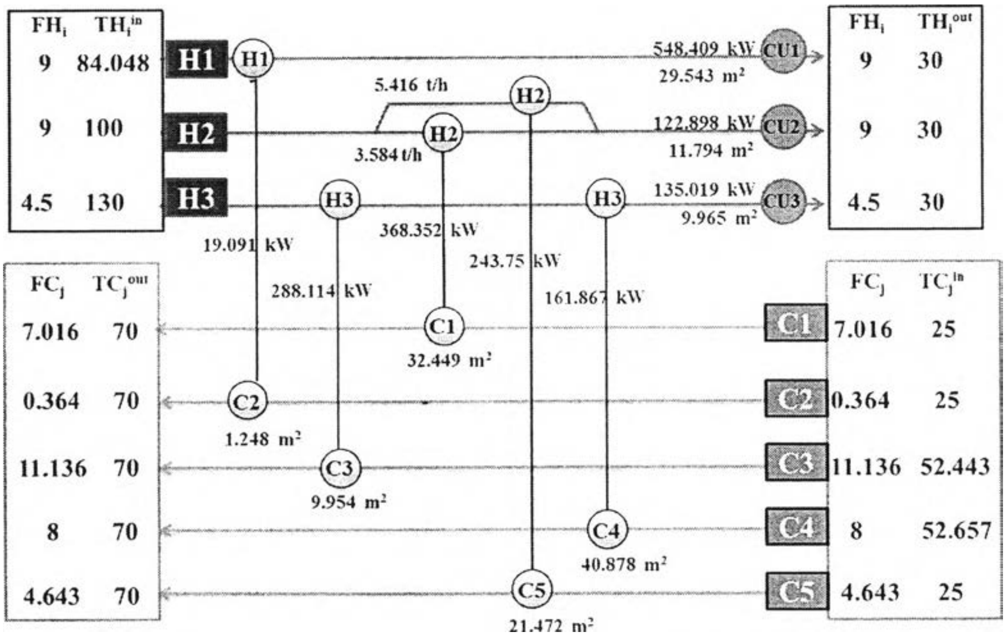

Figure 4.30 HEN in section 2 of WHEN by four-step design.

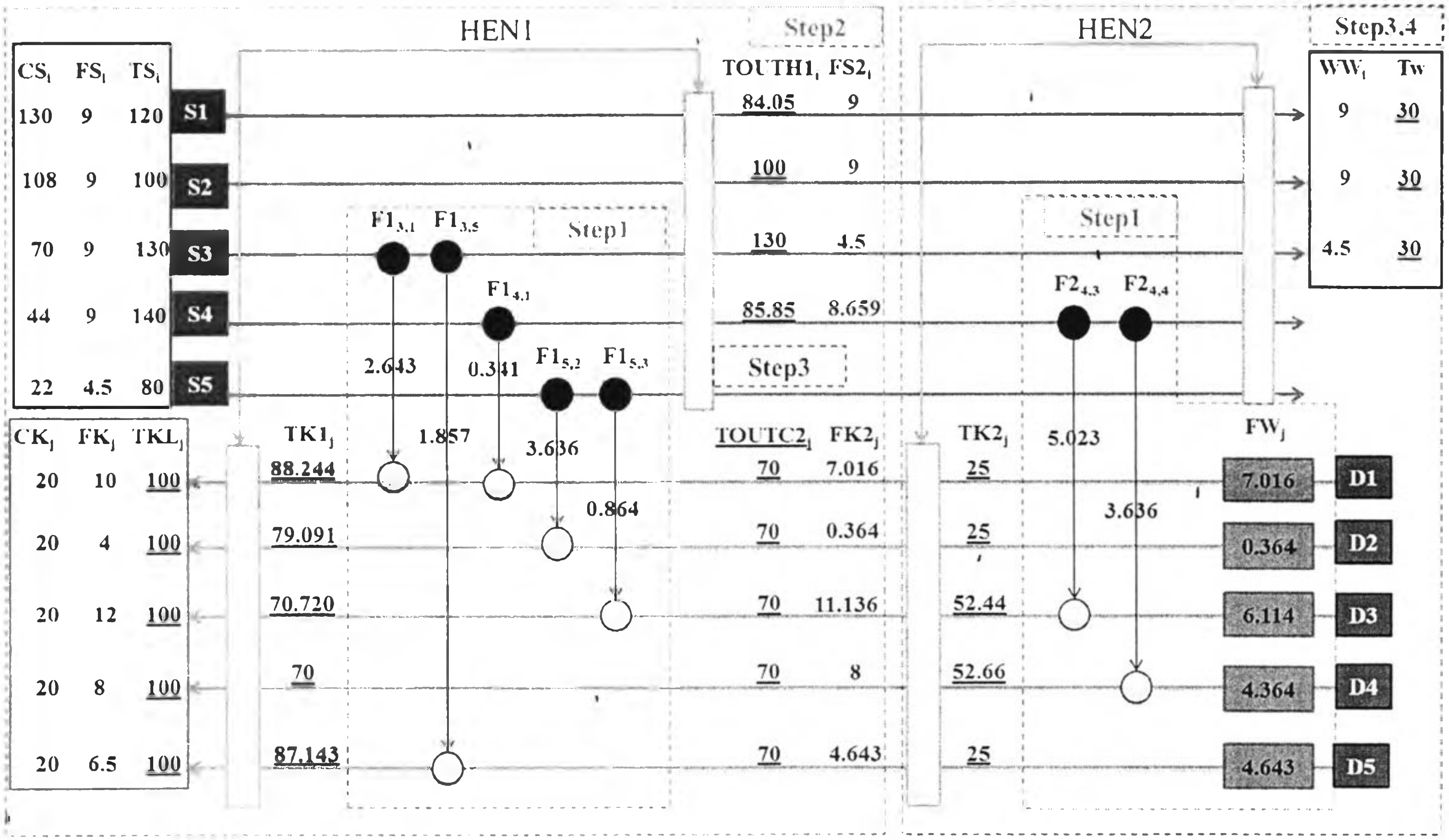

Figure 4.31 WHEN by four-step design.

Table 4.33 Results comparison of case study 4

Results	Based case	WN	HEN	WHEN by two-step	WHEN by four-step
Freshwater flowrate (t/h)	40.5	22.5	40.5	22.5	22.5
Wastewater flowrate (t/h)	40.5	22.5	40.5	22.5	22.5
Hot utility (kW/y)	3,543.75	1,496.25	0	268.41	97.576
Cold utility (kW/y)	4,147.50	2,205.00	603.75	977.16	806.33
Numbers of exchangers	10	8	11	12	13
Exchangers total area (m2)	317.16	180.518	474.379	558.56	262.97
Freshwater cost ($/y)	121,500	67,500	121,500	67,500	67,500
Piping annual cost ($/y)	2,637.60	3,353.68	2,637.60	3,353.68	3,353.68
Hot utility cost ($/y)	1,335,993.75	564,086.25	0	101,190.24	36,786.06
Cold utility cost ($/y)	783,877.50	416,745.00	114,108.75	184,683.07	152,395.57
Exchangers total annual cost ($/y)	99,014.31	77,852.34	157,808.83	131,433.64	125,946.13
Total annual cost ($/y)	2,343,023.16	1.129,537.27	396,055.18	488,160.63	385,981.43