CHAPTER II
THEORETICAL BACKGROUND AND LITERATURE REVIEW

2.1 Mathematical Models and Data for Water Network Problem

Water is an important material used in many processes. If the processes uses more water it will cost more money. A way to reduce water usage is to create the water network by using mathematical programming for calculating the optimal water usage and waste water discharge of each process. It needs some data for mathematical programming as follows:

2.1.1 Contaminants

The particles, that make the water impure, are called contaminants. Contaminants include all chemicals and other substances, Sieniutycz *et al.*, (2009), such as solid phase suspensions transferred in water-using processes and treatment operations following environmental regulations.

2.1.2 Freshwater/Raw Water Sources

Freshwater, which is very pure or contains very low contaminants, is used in mainly industrial process as a raw water sources for process. Freshwater is used in terms of water flow rates and it has cost unit for each source. Water after being used in process will be sent to treatment process for removing contaminants before reuse or discharge to environment.

2.1.3 Water-using Processes

The number of water-using processes is considered a fixed parameter in all contributions. However, models of processes differ. (Wang *et al.*, 1994) introduced mass transfer water-using processes, also called “quality controlled” operations. Many other authors have adopted the model. This is a simple counter-current mass exchanger (p) in which given loads of contaminants i(L^{i}_{p}) are transferred to a water stream from a real or a fictitious process stream as shown in Fig. 2.1

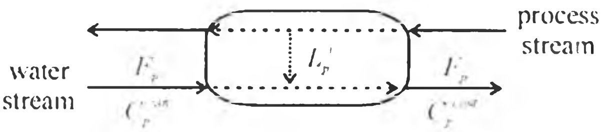

Figure 2.1 Scheme of water-using process *p* modeled as mass exchanger from Sieniutycz *et al.*, (2009).

Because contaminant concentrations are very small, the assumption of a constant flow rate of both streams is most often acceptable. Thus, the water stream mass balance equation of contaminant i in process p is:

$$L^i_p = F_p(C^{i,out}_p - C^{i,in}_p) \tag{2.1}$$

Concentrations of contaminants in process streams are known from process conditions. Hence, maximal allowable contaminant concentrations in water streams can be estimated from equilibrium conditions. In some cases such as equipment washing these concentrations depend on solubility, fouling or corrosion limits. To account for process kinetics the equilibrium concentrations are reduced by a small value. Let equilibrium concentration of specie i in water stream be C^{i*}. Then, maximum allowable concentration is: $C^{i*} - \varepsilon$. It is interesting to note that parameter ε plays a similar role to ΔT^{min} (HRAT) in heat integration. In the following we will apply concentrations in a shifted concentration scale, which is, reduced by parameter ε. Note also that an identical model has been applied by El-Halwagi *et al.*, (1997) for general mass exchanger networks.

Thus, for mass transfer water-using processes the following data are required for each mass transfer water-using process p and each contaminant i:

- Mass loads of contaminants L^i_p
- Maximum permissible inlet concentration of contaminants $C^{i,in,max}_p$
- Maximum permissible outlet concentration of contaminants $C^{i,out,max}_p$

Finally, the model of mass transfer process consists of balance equation (2.1) and inequalities (2.2) and (2.3):

$$C^{i,in}_{p} \leq C^{i,in,max}_{p} \tag{2.2}$$

$$C^{i,out}_{p} \leq C^{i,out,max}_{p} \tag{2.3}$$

The basic model of Wang *et al.*, (1994) has been extended in some works by inclusion of water gains and losses as shown in Fig. 2.2. Most often either losses or gains have to be accounted for.

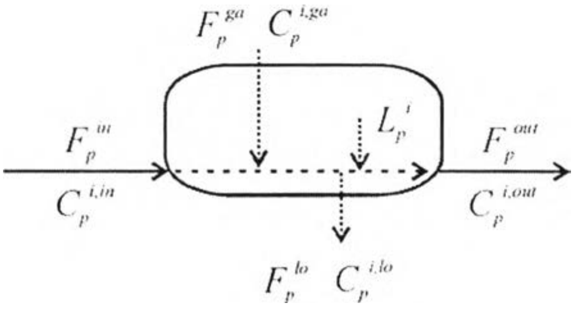

Figure 2.2 Water-using processes with water gains and losses from Sieniutycz *et al.*, (2009).

It is assumed that parameters F^{ga}_{p}, $C^{i,ga}_{p}$, F^{lo}_{p}, $C^{i,lo}_{p}$ are known and, thus, balance equation (2.1) becomes:

$$L^{i}_{p} = F^{in}_{p}\, C^{i,in}_{p} - F^{out}_{p}\, C^{i,out}_{p} + F^{ga}_{p}\, C^{i,ga}_{p} - F^{lo}_{p}\, C^{i,lo}_{p} \tag{2.4}$$

Inequality constraints (2.2) and (2.3) have to be added, too.

Dhole *et al.*, (1996) noticed that not all water-using processes in a process system can be modeled as mass exchangers. Chemical reactions, which use water as reagents or generate water as product, are an example. Also, cooling water cycles and boiler cycles are only consumers of make-up water. There are no mass transfer processes in such equipment. These processes are often called "quantity controlled water-using processes". We will refer to them in the following as non-mass transfer processes. Generally, they can be modeled as sources and/or sinks (demands) of water streams. Notice also that chemical sites in eco-parks and various operations by urban water consumers are most often referred to as sources and demands.

Generally, water sources have a fixed water stream flow rate and fixed concentrations of contaminants. Water sinks also feature fixed flow rates but contaminant concentrations are variables albeit limited by given maximal values. Water sources and sinks are illustrated by Fig. 2.3(a) and (b).

Note that if a process is water sink and water source at the same time it can also be represented by two items: single sink and single source.

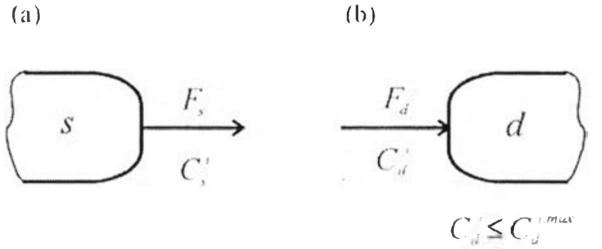

Figure 2.3 Representation of non-mass transfer processes as source and sink: (a) Water source s; (b) Water sink d. from Sieniutycz *et al.*, (2009).

Some other situations can exist, too. Assume that a water-using process is a mass transfer one but flow rate is fixed due to, for example, hydrodynamics restrictions. For instance, Wang *et al.*, (1995) have also considered such a condition. Thus, if contaminant mass loads and water stream flow rate are fixed, the only variables are contaminant concentrations. Such processes can also be modeled by a pair: sink and source. Prakash *et al.*, (2005) considered processes named "fixed flow rate" that have fixed but different values of flow rate at inlet and outlet. They can also be treated as source and sink. Dunn *et al.*, (2001) claimed that in industrial retrofit conditions even inlet and outlet concentrations should be fixed. Representation of sink and source can also be applied to the last case, but there are no degrees of freedom since all parameters are fixed.

2.1.4 Water Treatment and Disposal

Satisfactory disposal of wastewater, Rosa *et al.*, (2000), whether by surface, subsurface methods or dilution, is dependent on its treatment prior to disposal. Adequate treatment is necessary to prevent contamination of receiving waters to a degree which might interfere with their best or intended use, whether it be for water supply, recreation, or any other required purpose.

Wastewater treatment, however, can also be organized or categorized by the nature of the treatment process operation being used; for example, physical, chemical or biological. Examples of these treatment steps are shown below. A complete treatment system may consist of the application of a number of physical, chemical and biological processes to the wastewater.

Physical methods include processes where no gross chemical or biological changes are carried out and strictly physical phenomena are used to improve or treat the wastewater.

Examples would be coarse screening to remove larger entrained objects and sedimentation (or clarification). In the process of sedimentation, physical phenomena relating to the settling of solids by gravity are allowed to operate.

Chemical treatment consists of using some chemical reaction or reactions to improve the water quality. Probably the most commonly used chemical process is chlorination. Chlorine, a strong oxidizing chemical, is used to kill bacteria and to slow down the rate of decomposition of the wastewater. Bacterial kill is achieved when vital biological processes are affected by the chlorine. Another strong oxidizing agent that has also been used as an oxidizing disinfectant is ozone.

A chemical process commonly used in many industrial wastewater treatment operations is neutralization. Neutralization consists of the addition of acid or base to adjust pH levels back to neutrality. Since lime is a base it is sometimes used in the neutralization of acid wastes.

Biological treatment methods use microorganisms, mostly bacteria, in the biochemical decomposition of wastewaters to stable end products. More microorganisms, or sludge, are formed and a portion of the waste is converted to carbon dioxide, water and other end products. Generally, biological treatment methods can be divided into aerobic and anaerobic methods, based on availability of dissolved oxygen.

The purpose of wastewater treatment is generally to remove from the wastewater enough solids to permit the remainder to be discharged to receiving water without interfering with its best or proper use. The solids which are removed are primarily organic but may also include inorganic solids. Treatment must also be provided for the solids and liquids which are removed as sludge. Finally, treatment to control odors, to retard biological activity, or destroy pathogenic organisms may also be needed.

Material balance of specie i for treatment/regenerator *t* is given by equation (2.5) see also Fig. 2.4 for symbols:

$$L^{i}_{t} = F_t(C_t^{i,in} - C_t^{i,out}) \qquad (2.5)$$

Note that constant flow rate is assumed similar to balance (2.1) of the water using process. There are two simple design equations commonly used in the literature.

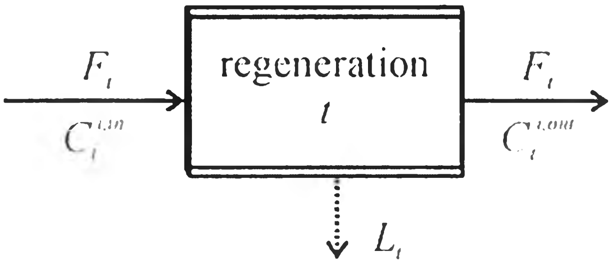

Figure 2.4 Scheme of regeneration/treatment process from Sieniutycz *et al.*, (2009).

Galan *et al.*, (1998) contributed with a detailed model of specific treatment operation in frames of WTN synthesis. Equation (2.6) fixes concentrations of some or all contaminants at the outlet. The outlet concentrations $C_t^{i,out*}$ are independent of flow rate and also of inlet conditions. Concentrations are parameters of the model:

$$C_t^{i,out} = C_t^{i,out*} \qquad (2.6)$$

Equation (2.7) defines recovery ratio of some or all contaminants in a process. These ratios are assumed to be known:

$$\Psi^{i}_{t} = (F_t C_t^{i,in} - F_t C_t^{i,out})/F_t C_t^{i,in} = L^{i}_{t} F_t C^{i,in} \qquad (2.7)$$

Some other conditions can be included. For instance, inequality limits inlet concentration of selected or all substances. Also, total flow rate of wastewater stream through treatment/regeneration unit can be limited by Equation (2.9):

$$C^{i,in}_{t} \leq C_t^{i,in,max} \qquad (2.8)$$

$$F_t \leq F_t^{max} \qquad (2.9)$$

It is most often assumed in approaches for WNRR, TWN and WTN that treatment/regeneration processes are known.

The number of wastewater disposal sites is known. For each site *w*, the limiting, environmental concentrations for each contaminant have to be given in equation (2.10). Additional conditions on allowable maximum wastewater flow rate can be added in equation (2.11). More complex conditions on water disposal to irrigation pools were applied only in Wenzel *et al.*, (2002):

$$C^{i} \leq C^{i,e}_{w} \qquad (2.10)$$

$$F_w \leq F_w^{max} \qquad (2.11)$$

2.2 Overview of Approaches in the Literature

2.2.1 Insight-based Approaches to Water Network

Sieniutycz *et al.*, (2009) approaches to water network using water pinch concept seem to be the most popular in the first times. Wang *et al.*, (1994) developed a graphical procedure for targeting a minimum freshwater flow rate for water networks consisting of mass exchange water-using processes. The water pinch targeting method for water-using processes of mass transfer type will be described applying the simple Example 2.1 taken from Wang *et al.*, (1994)

Table 2.1 Data for Example 2.1

Process number	**1**	**2**	**3**	**4**
Contaminant mass load (kg/h)	2	5	30	4
C^{max}_{in} (ppm)	0	50	50	400
C^{max}_{out} (ppm)	100	100	800	800

For Example 2.1 the data for this example are shown in Table 2.1 Let us emphasize that the data in Table 1 represent limiting data, i.e. maximum inlet and outlet concentrations of contaminant. Also, in Table 2.1 we assume that the mass transfer is a linear function of concentration. This is usually valid in dilute systems. However, if the behavior is significantly non-linear the approach can still be used by representing the non-linear process as a series of linear segments.

For each process the mass loads of the contaminant and the maximal values of inlet and outlet concentrations in water streams are given in the Table (notice that they are in shifted concentration scale). It is assumed that there is a single freshwater source and contaminant concentration in this freshwater is 0.0. Using the data we can simply calculate total freshwater usage for a parallel arrangement such as that in Fig. 2.1. For each process p=1, . . ., 4 in the parallel network the minimum flow rate of freshwater amounts to:

$$F_{fw,p} = L_p/(C_p^{in,max} - C^0) \tag{2.12}$$

Notice that index i for contaminant was dropped since there is one contaminant in the example.

For Example 2.1 the values of freshwater flow rate are 20, 50, 37.5 and 5 t/h, respectively. The total flow rate of freshwater that has to be applied in the parallel arrangement without reuse is thus 112.5 t/h.

Mass load of contaminant in process p existing in interval j is calculated from:

$$L_p(j) = \Delta C(j)/(C_p^{out,max} - C_p^{in,max}) \qquad (2.13)$$

where ΔC (j) denotes concentration range of interval j.

Parameter $L_p(j)$ is equal to 0.0 if the concentration range in process p does not fall into the concentration range of interval j. Then, values of the total mass loads L (j) are determined from:

$$L(j) = \Sigma_{p \in P} L_p(j) \qquad (2.14)$$

In Example 2.1, values of L (j) are L (1)=1kg/h, L (2)=8kg/h, L (3) = 12kg/h, L (4) = 20kg/h, respectively. Cumulative loads are then calculated by summing up values of L (j) in successive intervals. In Example 2.1 they are 1, 9, 21, and 41 kg/h.

The minimization of water flow rate overall, we must analyze how the water-using processes behave in an overall sense. For this we can construct a limiting composite curve as shown in Fig. 2.5

Fig. 2.5 indicates that the minimum water flow rate for Example 2.1 is 90 t/h compared with the 112.5 t/h the parallel arrangement without reuse, a reduction of 20%. For this target to be meaningful we must be able to achieve the target flow rate in a design in which the concentrations do not exceed the maximum inlet and outlet concentrations and features the same mass load as the data in Table 2.1.

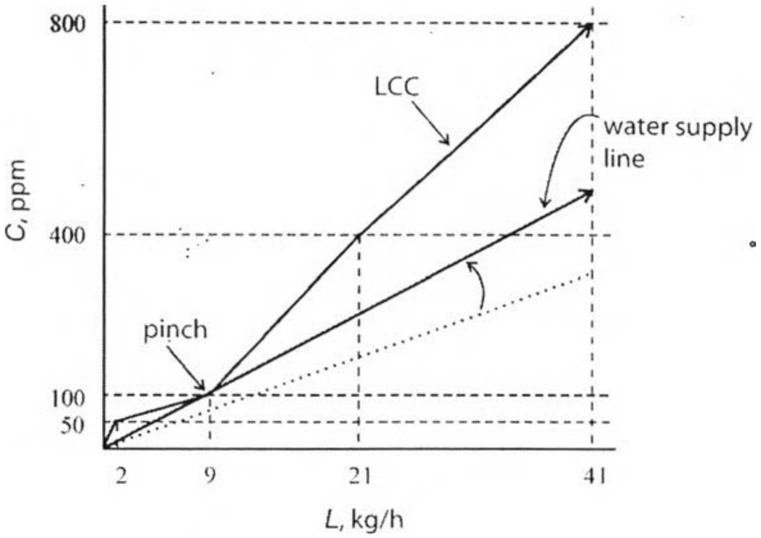

Figure 2.5 Water composite curve plot for Example 2.1 from Sieniutycz *et al.*, (2009).

Prakash *et al.*, (2005) are illustrating the new targeting approach, an example of a fixed flow rate or non-mass transfer process problem is considered. The data for the four demand streams and the four source streams in Example 2.2 are given in Table 2.2. Since the demands and sources have fixed flow rates specified by the problem definition, the constraints given in terms of contaminant concentrations can also be expressed in terms of contaminant loads. For example, if a demand has a specified flow rate of 50 t/h and a contaminant concentration limit of 20 ppm, the unit cannot have a contaminant intake of more than 1 kg/h.

Table 2.2 Data for Example 2.2

Demands and Sources	Contaminant concentration (ppm)	Flow rate (t/h)
D1	20	50
D2	50	100
D3	100	80
D4	200	70
S1	50	50
S2	100	100
S3	150	70
S4	250	60

To construct the demand and source composite curves, the first step is to arrange the demands and sources in increasing order of contaminant concentration. Then, the cumulative flow rates and contaminant loads are calculated as shown in Table 2. The plot of cumulative contaminant load vs. cumulative flow rate yields the demand and source composite curves shown in Fig. 2.6

The contaminant load of the source should be less than or equal to the contaminant load of the demand at every point in Fig. 2.6(a) to meet the contaminant concentration constraint. This is ensured by translating the source composite curve horizontally until it is just below the demand composite curve as in Fig. 2.6(a)

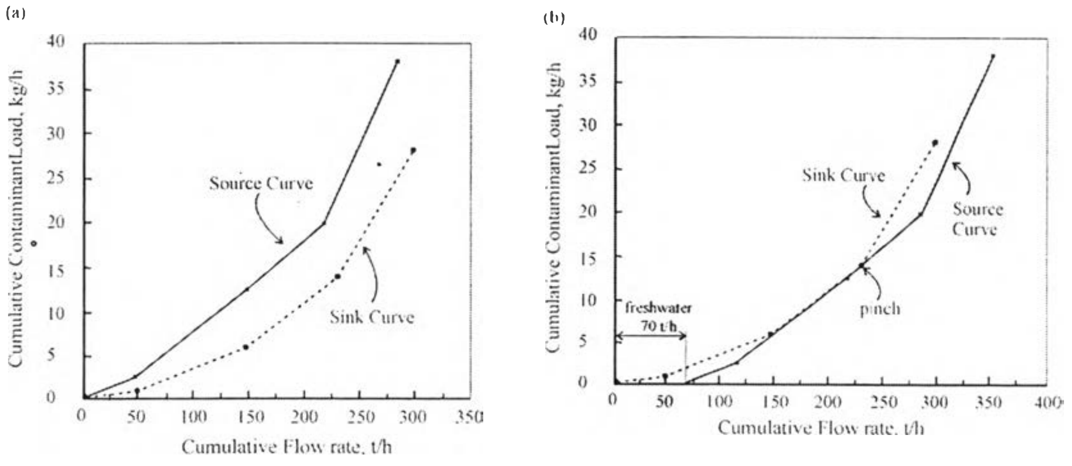

Figure 2.6 Plot for determining the minimum freshwater flow rate for Example 2.2: (a) Source and sink curves before shifting; (b) Source and sink curves after shifting.

The point at which the two curves touch each other is the pinch. Horizontal shifting of the source composite implies an increase in the cumulative flow rate without any increase in the contaminant load. This is possible only by the addition of freshwater to the source streams. Hence, the minimum horizontal shift required to bring the source composite just below the demand composite gives the minimum freshwater target. The portion of the source composite not overlapped by the demand composite gives the wastewater target. From Fig. 2.6(b), the freshwater and wastewater targets for Example 2.2 are 70 and 50 t/h, respectively. The pinch occurs at a flow rate of 230 t/h and a contaminant load of 14 kg/h. Demands D1, D2 and D3 are below the pinch, while D4 is above the pinch. Among the sources, S0 (i.e., freshwater), S1, S2 and 10 t/h of S3 are below the pinch, while 60 t/h of S3 and S4 are above the pinch.

Table 2.3 Results of calculations

Demands and Sources	Contaminant load (kg/h)	Cumulative Flow rate (t/h)	Cumulative load (kg/h)	Cumulative flow rate for minimum freshwater intake (t/h)
D1	1	50	1	-
D2	5	150	6	
D3	8	230	14	
D4	14	300	28	
S0	0	0	0	70
S1	2.5	50	2.5	120
S2	10.0	150	12.5	220
S3	10.5	220	23.0	290
S4	15.0	280	38.0	350

Then, S0 = Fresh water

However, a simple alternative to the Problem Table Algorithm is the method outlined below based on Table 2.3 and Fig. 2.6(a). Recall that the pinch can occur only at a demand vertex. Therefore, the horizontal distance between the two composite curves in Fig. 2.6(a) may be simply calculated at each demand vertex by linear interpolation of the source composite curve data in Table 3. The distance is negative if the source composite is to the left of the demand composite and vice versa. Then, the most negative value of the horizontal distance specifies the minimum freshwater target. Linear interpolation of the source composite curve data in Table 3 gives the cumulative source flow rates (in t/h) to be 20, 85, 160 and 240 at the four demand vertices. The horizontal distances (in t/h) between the two composites at the demand vertices are −30, −65, −70 and −60. Then, the most negative value of −70 gives the minimum freshwater target as 70 t/h for Example 2.2. Thus, the targeting procedure is completely analytical with simple hand calculations being performed in a tabular form without any graphical construction.

2.2.2 Optimization-based Approaches to Water Network

Sieniutycz *et al.*, (2009) are approaches the majority of optimization-based by apply superstructure optimization. It uses the mathematical programming techniques to optimize water network design. The main aim of the model was targeting freshwater usage but the results also provide certain structural features that can be applied to develop the final network.

The optimization-based approaches can explain by using the superstructure concept. The superstructure is including splitter, mixer, process, regeneration process or treatment process. The symbols of each unit are explained in Fig. 2.7 and the scheme of water network superstructure is shown in Fig. 2.8

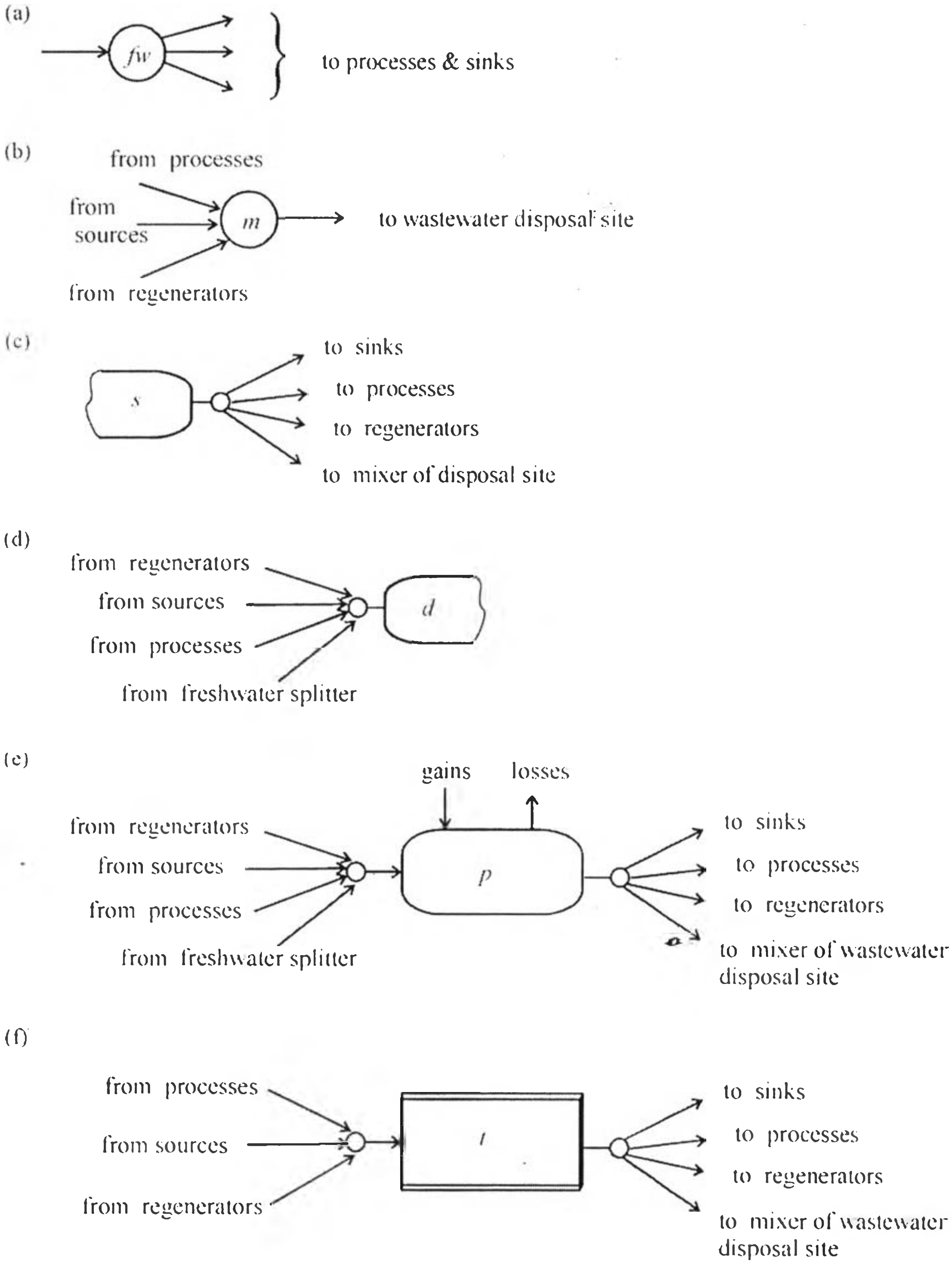

Figure 2.7 Building blocks of water network superstructure:

(a) Freshwater splitter.	(d) Sink of non-mass transfer process.
(b) Mixer of wastewater disposal site.	(e) Mass transfer process.
(c) Source of non-mass transfer process.	(f) Treatment/regeneration process.

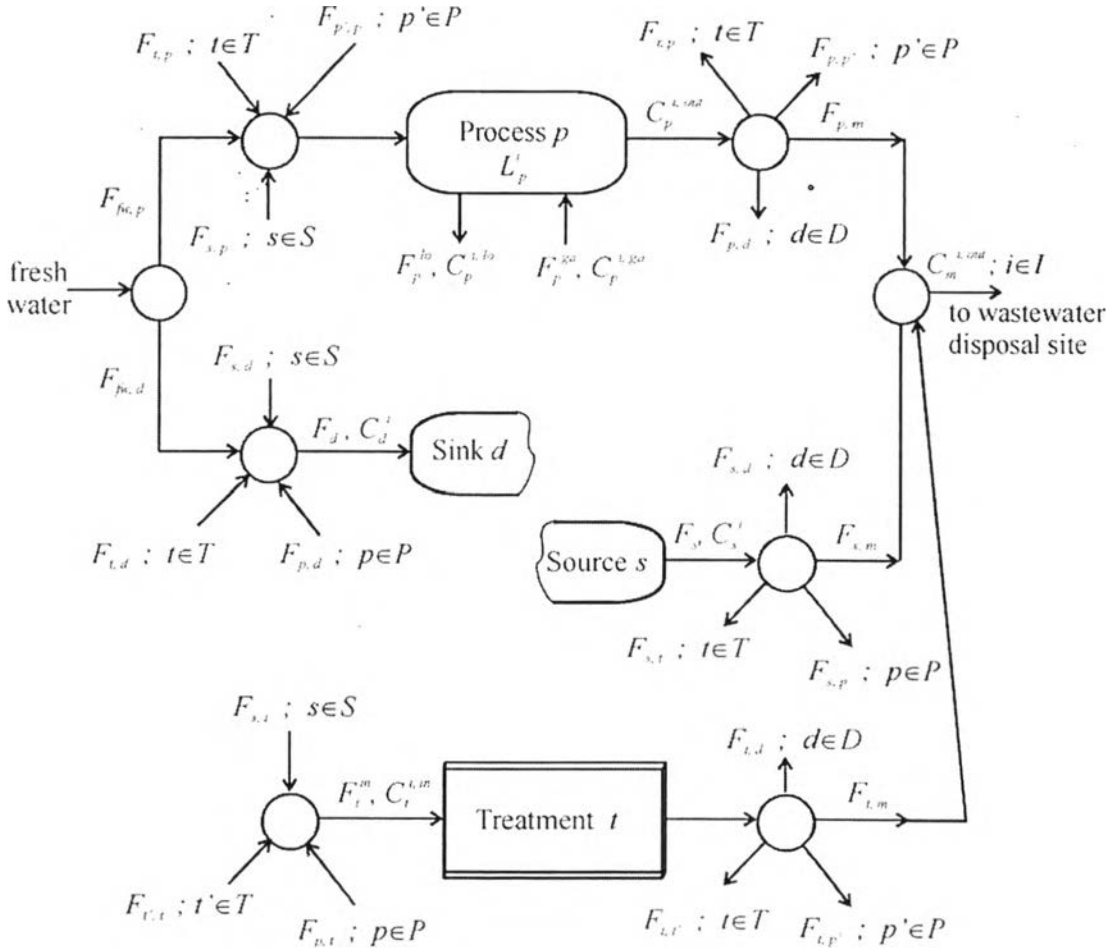

Figure 2.8 Scheme of water network superstructure from Sieniutycz *et al.*, (2009).

Parameters:

AR : annualized factor for investment on treatment units

C^{i}_{fw} : contaminant i concentration in freshwater source

$C^{i,e}$: contaminant i limiting concentration in wastewater stream to environment

$C_p^{i,in,max}$ /$C_p^{i,out,max}$: maximum value of inlet/outlet contaminant i concentration in mass transfer water using processes p

$C_p^{i,ga}$ /$C_p^{i,lo}$: contaminant i concentration in gains/losses in mass transfer water-using process p

$C_t^{i,in,max}$: maximum permissible inlet concentration of contaminant i at the inlet to treatment/regeneration processes t

C^{i}_{s}/F^{s} : contaminant i concentration/flow rate for source s

$C_d^{i,max}/F_d$: maximum contaminant i concentration/flow rate for sink d

$C_t^{i,out}$: outlet concentration of contaminant i at the outlet from treatment/ regeneration process t

F_p^{ga} /F_p^{lo} : flow rate of gains/losses in mass transfer water-using processes p

F_t^{max} : maximum permissible flow rate via treatment/regeneration process t

F^{*} : sufficiently large number, higher than any possible flow rate in the network

H : time of operation per year

L^{i}_{p} : mass load of contaminant i transferred to water in mass transfer water using process p

α_{fw} : unit cost of freshwater

$\beta_{fw,p}/\beta_{fw,d}$: fixed cost of piping section from freshwater splitter f_w to mass transfer water-using process p/sink d

$\beta_{t,t'}$ /$\beta_{t,p}/\beta_{t,m}/\beta_{t,d}$: fixed cost of piping section from treatment process t to treatment process t' /mass transfer water-using process p/mixer of disposal site m/sink d

$\beta_{p,p'}$ /$\beta_{p,t}$/$\beta_{p,s}$/$\beta_{p,m}$: fixed cost of piping section from mass transfer water using processes p to: mass transfer water-using process p' /treatment t/source d/mixer of wastewater disposal site m

$\beta_{s,p}$/$\beta_{s,t}$/$\beta_{s,d}$/$\beta_{s,m}$: fixed cost of piping section from source s to mass transfer water-using processes p/treatment t/sink d/mixer m of wastewater disposal site.

The optimization model of the superstructure for the water network problem is given in the following. To model processes, mixers and splitters we have adapted the formulations of Bagajewicz *et al.* (2000). The equations are written for arrangements: mixer–process–splitters, mixer–treatment–splitter rather than for individual equipment. Also, flow rates are employed in modeling splitters instead of split ratios. This was also advised by Karuppiah *et al.*, (2006). Additionally, application of flow rates is advantageous in the stochastic optimization approach addressed.

Bagajewicz *et al.* (2000) designed procedures for water networks in refineries and process plants. It is shown in Fig. 2.9 how the wastewater treatment problem was model as a distributed and decentralized treatment.

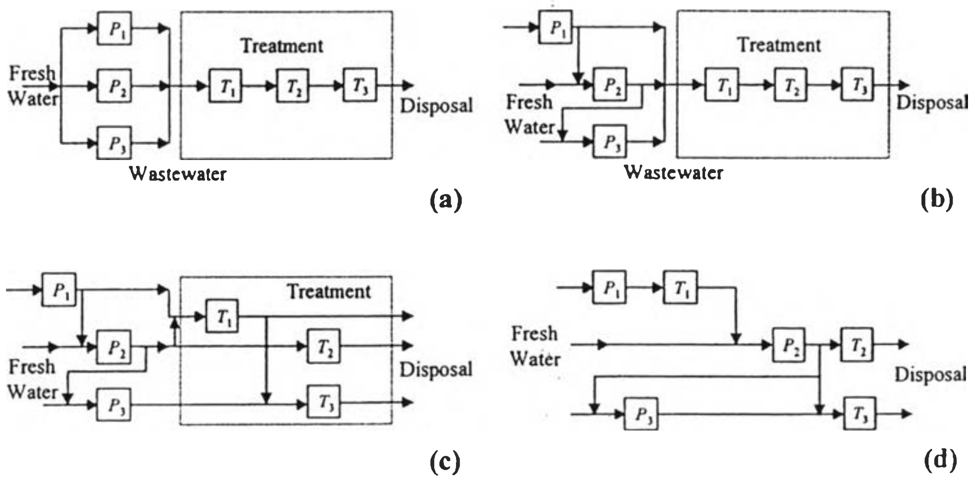

Figure 2.9 Water utilization systems in process plants from Bagajewicz *et al.* (2000).

A system is depicted for 3 water user processes and 3 treatments unit in Fig. 2.9(a). The first way to improve this design is the reuse of wastewater that outlet from each processes to feed another without sending it to treatment first Fig. 2.9(b). The next is designs of the wastewater treatment unit without merging all the wastewater streams Fig. 2.9(c). Finally, treatment can be decentralized in such a way that some pollutants are removed from wastewater of selected processes allowing the reuse of these waters Fig. 2.9(d).

Doyle *et al.* (1997) designed a method for targeting water reuse with multiple contaminants in terms of fixed mass load with non-liner optimization and fixed outlet concentration with liner optimization. It show in Example 2.3

Table 2.4 Limiting process data for Example 2.3

Operation	Limiting water flow rate (t/h)	Contaminants	$C^{in.max}$ (ppm)	$C^{out.max}$ (ppm)
1	45	Hydrocarbon	0	15
		H_2S	0	400
		Salt	0	35
2	34	Hydrocarbon	20	120
		H_2S	300	12,500
		Salt	45	180
3	56	Hydrocarbon	120	220
		H_2S	20	45
		Salt	200	9,500

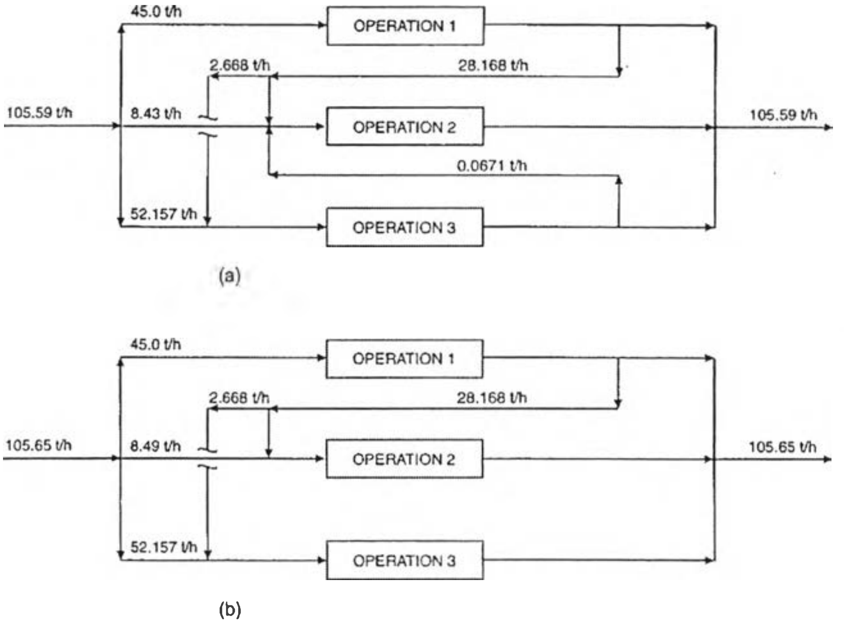

Figure 2.10 Design for Example 2.3: (a) Design for minimum flow rate of fresh water ; (b) Design with the smallest reuse eliminated.

The first assumption is outlet concentrations are fixed to maximum values and use the liner programming to create water network structure and find the final answer by optimize the objective function. The structure which results from the optimization is shown in Fig. 2.10(a). It can be seen that one of the connections is particularly small, showing a reuse of 0.067 t/h which would be uneconomic. However, we can easily add a constraint to eliminate this match and forbid reuse from operation 3 to operation 2. This result in a new target of 105.65 t/h, that comes from the second assuming is fixed mass load and use the non-liner programming. The structure which results from the optimization is shown in Fig. 2.10(b). The solution from the linear model can provide an initialization for non-linear optimization for the fixed mass load case or the combined case.

Prakash *et al.* (2005) designed the method for targeting the minimum freshwater and pinch in a single-contaminant water network is proposed. The pinch method was shown earlier in Example 2.2 and the second method is minimum freshwater by nearest neighbors algorithm (NNA) is shown in Example 2.4

Table 2.5 Data for Example 2.4

Demands and Sources	Contaminant concentration (ppm)	Flow rate (t/h)
D1	20	50
D2	50	100
D3	100	80
D4	200	70
S1	50	50
S2	100	100
S3	150	70
S4	250	60

The data for Example 2.4 is shown in Table 2.5 is the same data in Example 2.2. From the NNA method, the final network is shown in Fig. 2.11

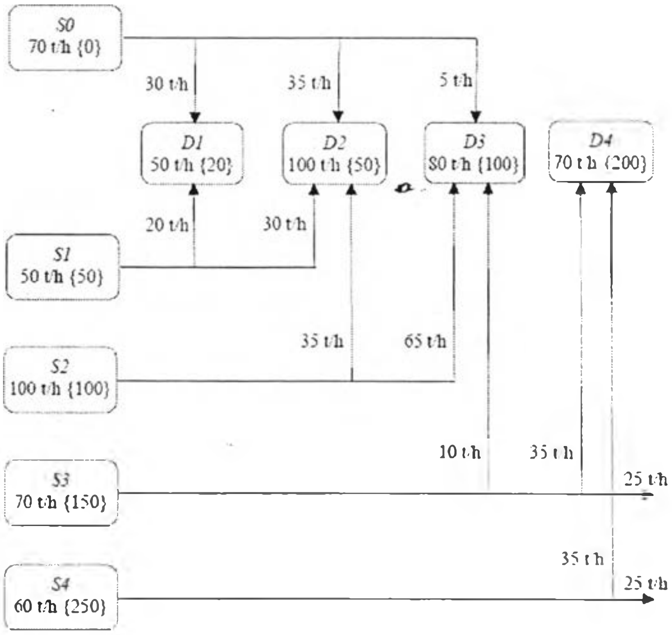

Figure 2.11 Minimum freshwater network for Example 2.4 by NNA from Prakash *et al.* (2005).

From NNA method, the freshwater flow rate is 70 t/h and wastewater flow rate is 50 t/h. It the same answer in Example 2.2. It mean the pinch model is first way to guess the values of freshwater usage and wastewater.

Faria *et al.* (2008) designed the method for optimizing the multicomponent water/wastewater networks. It used non-liner programming to discretize one of the variables of the bilinear terms. The main objection function is minimizing fresh water usage. It is shown in Example 2.5

The first optimization result contains 6 water-using units without regeneration process and data from Table 2.6. The solution when freshwater consumption is minimized is presented in Fig. 2.12. A freshwater consumption is 119.332 t/h and wastewater is 119.332 t/h.

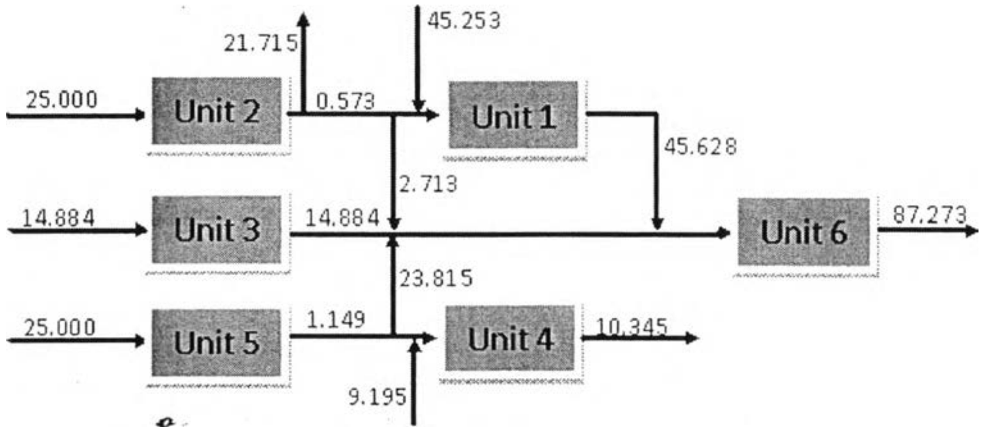

Figure 2.12 Optimal design for multicomponents for Example 2.5 without regeneration from Faria *et al.* (2008).

The second optimization result contains 6 water-using unit and 3 regeneration processes. The data is obtained from Table 2.6 and 2.7

Table 2.6 Water using units data for Example 2.5

Process	Contaminants	$C^{in,max}$ (ppm)	$C^{out,max}$ (ppm)	Load (kg/h)
(1) Caustic treating	Salt	300	500	0.18
	Organic	50	500	1.20
	H_2S	5,000	11,000	0.75
	Ammonia	1,500	3,000	0.10
(2) Distillation	Salt	10	200	3.61
	Organic	1	4,000	100.0
	H_2S	0	500	0.25
	Ammonia	0	1,000	0.50
(3) Amine sweetening	Salt	10	1,000	0.60
	Organic	1	3,500	30.0
	H_2S	0	2,000	1.50
	Ammonia	0	3,500	1.00
(4) Sweetening (Merox I)	Salt	100	400	2.00
	Organic	200	6,000	60.0
	H_2S	50	2,000	0.80
	Ammonia	1,000	3,500	1.00
(5) Hydrotreating	Salt	85	350	3.80
	Organic	200	1,800	45.0
	H_2S	300	6,500	1.10
	Ammonia	200	1,000	2.00
(6) Desalter	Salt	1,000	9,500	120.0
	Organic	1,000	6,500	480.0
	H_2S	150	450	1.50
	Ammonia	200	400	0.00

Table 2.7 Regeneration processes data for Example 2.5

Process	**Contaminants**	$C^{out.max}$ **(ppm)**	**Cost ($/t)**
(7) API separator followed by ACA	Salt	No treat	$0.12^{a,b}$
	Organic	50	
	H_2S	No treat	
	Ammonia	No treat	
(8) RO	Salt	20	0.56^{a}
	Organic	No treat	
	H_2S	No treat	
	Ammonia	No treat	
(9) Chevron waste water treatment	Salt	No treat	1.00^{c}
	Organic	No treat	
	H_2S	5	
	Ammonia	30	

Then,

a Source: Perry *et al.*, (1997).

b Source: Stenzel *et al.*, (1993).

c Source: Leonard *et al.*, (1984).

The regeneration processes with fixed outlet concentrations of the key contaminants. The minimum freshwater consumption with regenerations is 33.571 ton/h. To convert it to a mathematical form, it needs the total removed contaminant mass load (that is the combination between flow rate and concentration reduction) as the objective function. The regeneration processes have the following features: Reverse osmosis is for reducing salts to 85 ppm instead 20 ppm originally proposed. The API separator followed by ACA is for reducing organics to 50 ppm as before. Finally, the Chevron wastewater treatment should keep the 5 ppm in reduction for H2S, but operate to reduce ammonia to 120 ppm instead 30ppm. The suggested network is presented in Fig. 2.13.

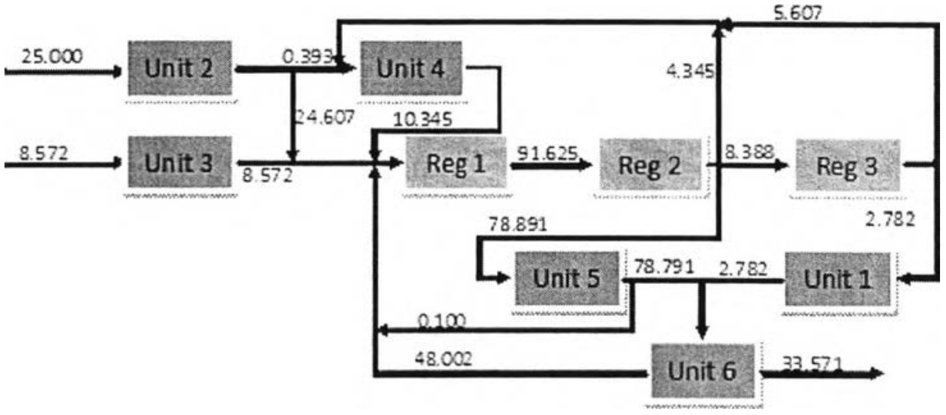

Figure 2.13 Optimum water network design for multicomponent for Example 2.5 with regeneration from Faria *et al.* (2008).

Liu *et al.*, (2013) designed the distributed wastewater treatment systems, wastewater degradation caused by unreasoning stream-mixing will increase the total treatment flow rate, and this will often increase treatment cost. The design procedure includes following 3 steps: (1) the main function of each treatment unit is identified; (2) the minimum treatment amount of each unit for its main contaminant, without considering other contaminants, is obtained with pinch method; (3) for the systems with many treatment units a three-unit-group is selected and the precedence order of the units in the group is determined with the heuristic rules. It shown in Example 2.6

The data for Example 2.6 are shown in Table 2.8. The environmental limit for each contaminant is 100 ppm. It is found three units to be executed first are TP_2, TP_3 and TP_4. The structure of the system is shown in Fig. 2.14

Next, The 3 outlet streams from first group ($S_{U2\text{-}P}$, S_{U2} and S_{U4}) are used in another treatment processes (TP_1 and TP_5) and optimized at the final design in Fig. 2.15

Table 2.8 Stream and treatment unit data for Example 2.6

Stream	Concentration (ppm)						Flow rate f_i
Stream data	A	B	C	D	E	F	(t/h)
1	1,100	500	500	200	800	100	19
2	40	0	100	300	910	200	7
3	200	220	200	500	150	0	8
4	60	510	500	200	780	100	6
5	400	170	100	300	900	0	17
	Removal ratio RR_i (%)						
Treatment unit	A	B	C	D	E	F	-
1	99						
2		99					
3			99				
4				99	90		
5					99	99	

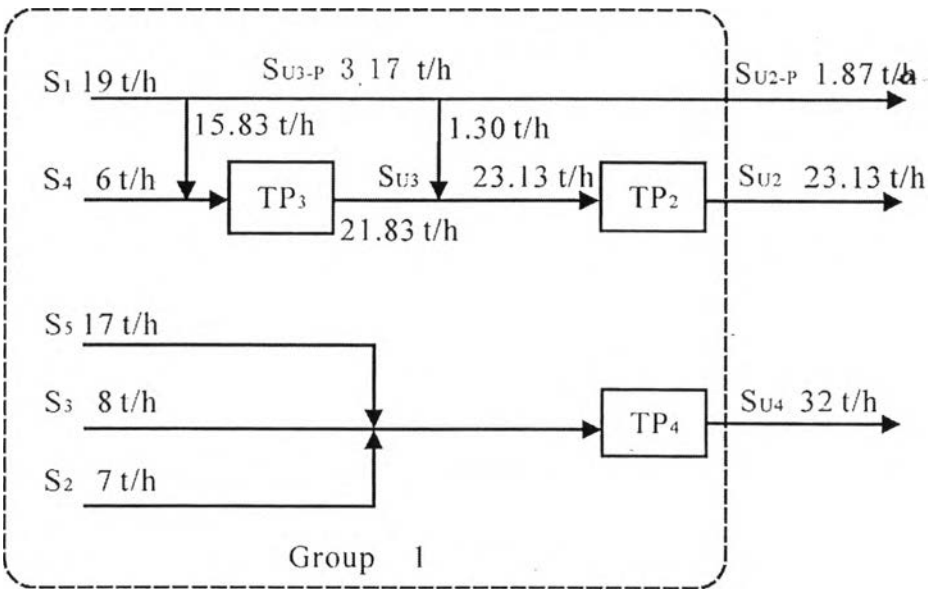

Figure 2.14 The streams in water network after the first group executed for Example 2.6 from Liu *et al.*, (2013).

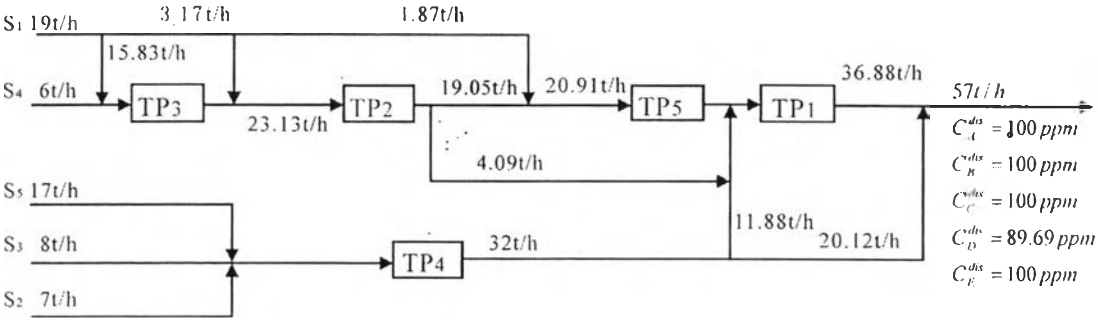

Figure 2.15 Final network design for Example 2.6 from Liu *et al.*, (2013).

This model is designed for a complex system, a three-unit group is selected and executed first based on the minimum-mixing rule. Then the next three-unit group will be selected and executed till the number of unexecuted units is less than three. In the selected group, the precedence order of the units can be determined based on the heuristic rules. Pinch method is used to calculate the minimum treatment amount of each unit for its main contaminant without considering other contaminants. It is shown that the method proposed in this work is simple and effective.