CHAPTER 5

RESULT AND DISCUSSION –
TIME-DEPENDENT WATER CASCADE ANALYSIS

5.1 Introduction

This chapter presents a two-stage procedure for the synthesis of maximum water recovery (MWR) network for a batch process system. The first stage of the synthesis task is to locate the various network targets, which include the minimum fresh water and wastewater flowrates (overall and interval-based targets) as well as storage capacity target using the newly developed *time-dependent water cascade analysis* (TDWCA) technique. The TDWCA technique is an extension of the water cascade analysis (WCA) technique presented in Chapter 4 of this thesis. In the second stage, a new tool called the *time-water network* is introduced to synthesis the MWR network to achieve the established network targets. This new network representation has an advantage of clearly depicting the time-dependent nature of a batch water network. Two literature case studies are used to demonstrate the above-mentioned two-stage procedure.

5.2 Time-dependent water cascade analysis

The seminal work of Kemp and co-workers (Kemp and Macdonald, 1987, 1988; Kemp and Deakin, 1989a, b) on batch heat integration provides the very basic foundation on how the conventional process integration technique could be applied to many industrial processes that are operated in batch mode. They showed that by dividing the time intervals where the process heat and cold streams exist, hot and cold utility targeting and network design could be carried out independently in these intervals. Foo *et al.* (2004, 2005) recently showed that the same analogy could be applied to batch mass integration. Hence, the approach for batch water network will also be built on the same principles of batch heat and mass integration.

Similar to any pinch-based approach in heat and mass integration, the first stage in synthesising a batch MWR network is to locate the various network targets ahead of the detailed network design. Note also that, in both batch heat and mass integration, numerical targeting approach is utilised to locate the minimum utility targets, in contrast to the common practise of graphical approach (e.g. composite curves, etc.). In this instance, time-dependent heat cascade analysis was utilised in batch heat integration (Kemp and Macdonald, 1987, 1988; Kemp and Deakin, 1989a); while time-dependant concentration interval table was utilised in batch mass integration (Foo *et al.*, 2004, 2005). This is due to the complex nature of batch process integration work. Often, one will need to repeat the utility targeting procedure independently for each time interval. Numerical approach produces accurate targets and reduces the time required for tedious drawings and calculations involved in the graphical approach.

In the next section, it will be demonstrated by appropriate modification, the WCA technique developed in Chapter 4 serves as a good targeting tool for a batch MWR network through a literature case study.

5.3 Example 5.1 - Kim and Smith (2004)

Table 5.1 shows the limiting water data for a case study taken from Kim and Smith (2004) that will be used to demonstrate the newly developed approach. This case study comprises of four mass transfer-based water-using operations with uniform mass flow at the inlet and outlet of each individual process. Chapter 4 of this thesis showed that the inlet and outlet flows of mass transfer processes are appropriately represented as the sinks and sources in the non-mass transfer model. In this instant, SK_1 and SR_1; SK_2 and SR_2; SK_3 and SR_3; SK_4 and SR_4 are sinks (SK_j) and sources (SR_i) for processes 1, 2, 3 and 4 respectively. Note also another characteristic of mass transfer-based processes is that, in batch operation mode, water sink and source of the water-using operation exist simultaneously with the main mass transfer operation. Besides, the starting (t^s) and the ending time (t^t) of each operation are also given, which in turn convert the water flowrate of each operation into its associated mass flow. Without water reuse, both fresh water and wastewater flow targets for this case study are calculated as 370 ton (given by the sum of water flow in final column of Table 5.1).

Table 5.1 Limiting water data for Example 5.1

Water sink, SK_j	**Flowrate, F_j (ton/h)**	**Concentration, C_j (ppm)**	**Starting time, t^s (h)**	**Ending time, t^t (h)**	**Water flow, M_j (ton)**
SK_1	20	0	0	1.0	20
SK_2	100	50	1.0	3.5	250
SK_3	40	50	3.0	5.0	80
SK_4	10	400	1.0	3.0	20
Water sources, SR_i	**Flowrate, F_i (ton/h)**	**Concentration, C_i (ppm)**	**Starting time, t^s (h)**	**Ending time, t^t (h)**	**Water flow, M_i (ton)**
SR_1	20	100	0	1.0	20
SR_2	100	100	1.0	3.5	250
SR_3	40	800	3.0	5.0	80
SR_4	10	800	1.0	3.0	20

As described in Chapter 3, the first step in the flow targeting stage is to locate the water sinks and sources at their respective time intervals in the *time interval table* (Table 5.2). Water flow of sink j (M_j) and source i (M_i) at interval l are assumed to exist in the intervals in proportion to the duration of the time interval (Δt_l). With the time interval table in place, one can clearly identify the existence of instantaneous water sinks and sources in each of these time intervals before any analysis is carried out. The time interval table will now be demonstrated to locate the various network targets in a batch water network, for system without water storage tank, and subsequently, for system with storage tank installed.

Table 5.2 Time interval table for Example 5.1

Time interval, *l*	**Time (hr)**	**Duration, Δt_l (hr)**	**Water sinks, M_j (ton)**	**Water sources, M_i (ton)**
1	0 - 1.0	1.0	$M_1 = 20$	$M_1 = 20$
2	1.0 - 3.0	2.0	$M_2 = 200$; $M_4 = 20$	$M_2 = 200$; $M_4 = 20$
3	3.0 - 3.5	0.5	$M_2 = 50$; $M_3 = 20$	$M_2 = 50$; $M_3 = 20$
4	3.5 - 5.0	1.5	$M_3 = 60$	$M_3 = 60$

5.3.1 Targeting for batch water network without water storage tank

As shown in the time interval table (Table 5.2), all time intervals consist of both water sinks and sources, which mean that *direct water integration* can occur in these intervals. A close observation indicates that water sinks and sources that exist in the same interval originate from the same water-using processes. This is mainly due to the fact that these water-using processes in the network are mass transfer-based operations, in which their water sinks and sources exist during the occurrence of the processes. Note however that this is not often the case. When non-mass transfer-based processes exist in the network, the water sinks and sources of these processes are often found in different time intervals. Often, only water sinks or sources are found in certain time intervals, which mean that no direct water integration occur in these intervals. Hence, either fresh water is needed to supplement the water sinks (when water sinks exist only) or wastewater is generated (water sources exist only) from these intervals.

Table 5.3 shows the flow targeting tool for Example 5.1, called the *time-dependent water cascade analysis* (TDWCA, adapted from Table 3.4), an extension to the WCA targeting technique presented in Chapter 4. The first column of Table 5.3 contains the impurity concentration levels (*C*) arranged in ascending order. Column 3 – 6 ($l = 1 – 4$) contain the mass flow of the water sinks and sources that exist in each time interval, at their corresponding concentration levels. In order to achieve the target for a MWR network, flow targeting is to be carried out in each time interval. This involves the use of WCA targeting technique, presented in Chapter 4 of this thesis.

Table 5.3 TDWCA for Example 5.1 (without water storage system)

Time interval	***l***	1	2	3	4	
	(hr)	0-1.0	1.0-3.0	3.0-3.5	3.5-5.0	
C_k **(ppm)**	$M_{F,l}$ **(ton)** ΔC_k	20	100	35	56.25	M_F = 211.25
0		-20				
	50					
50			-200	-70	-60	
	50					
100		20	200	50		
	300					
400			-20			
	400					
800			20	20	60	
	999,200					
1,000,000						
	$M_{D,l}$ **(ton)**	20	100	35	56.25	M_D = 211.25

Individual fresh water ($M_{F,\,l}$) and wastewater ($M_{D,\,l}$) targets for time interval *l*, or the *interval-based flow targets* are summarised in the second and final row of Table 5.3. Summing these individual targets yield the overall fresh water (M_F) and wastewater mass flow (M_D), both at 211.25 ton, given in the final column of Table 5.3. This represents a reduction of 42.9% for both water flows.

5.3.2 Targeting for Batch water network with water storage tank systems

In the batch process industry, processes are normally operated in repeated batches, with several storage tanks available throughout the operation. Water storage system is useful in minimising the operational cost by maximising water reuse among the batches of operation. Previous work on batch heat and mass integration showed that targets for repeated batch processes are exactly the same as in the case of a continuous process (Kemp and Deakin, 1989a; Foo *et al.* 2004). As a special case of batch mass integration, batch water network should also exhibits the same characteristic. Hence, this provides a better mean on how the problem could be handled.

The first key step in the time-dependent WCA for repeated batch processes is to establish the overall fresh water and wastewater flow targets for the entire network. Column 7 of Table 5.4 shows the *net interval mass flows* ($\Sigma_j M_j - \Sigma_i M_i$) for all water sinks and sources across all time intervals, at their corresponding concentration levels. Positive value of the mass flow represents *net water source*, and negative *net water demand*. Water flow and load cascade for the overall process is given in Column 8 and 9 respectively. As shown, overall fresh water (M_F) and the wastewater (M_D) mass flows are both determined as 185 ton. This resembles a reduction of 50% for both water flows, as compared to the original case study without water reuse scheme.

Table 5.4 Targeting overall fresh water and wastewater flows with TDWCA for Example 5.1 (network with water storage system)

Time interval	***l***	1	2	3	4	**$\Sigma_i M_i - \Sigma_j M_j$ (ton)**	**$M_{C,k}$ (ton)**	**Δm_k (kg)**	**Cum. Δm_k (kg)**
	(hr)	0-1.0	1.0-3.0	3.0-3.5	3.5-5.0				
C_k (ppm)	**$M_{F,l}$** **ΔC_k**	20	100	35	30				
							M_F = 185		
0		-20				-20			
	50						165	8.25	
50			-200	-70	-60	-330			8.25
	50						-165	-8.25	
100		20	200	50		270			**0 (PINCH)**
	300						105	31.50	
400			-20			-20			31.50
	400						85	34.00	
800			20	20	60	100			65.50
	999,200							184852.00	
1,000,000									184917.50
	M_{ST} (ton)	0	30	30	0				
	$M_{D,l}$ (ton)	20	70	35	60		**M_D = 185**		

In the final column of Table 5.4, zero cumulative load (cum. Δm_k) is observed at 100 ppm, where the *global pinch* of the network exists. Note that one should differentiate this global pinch with the interval-based pinch point that exist in each time intervals. For flow targeting in a batch MWR network, the global pinch concentration is of more important use as compared to the individual interval-based pinch points. The global pinch divides the overall network into two main thermodynamic regions, i.e. regions above and below the global pinch. Region above the pinch is the most constrained part of the network that represents the bottleneck for maximum water recovery. Besides, water sources at the pinch are termed as the pinch-causing streams, with a portion of the source belongs to the region above the pinch, while the rest, to region below the pinch. For this case study, out of 270 ton of water sources at the pinch, 165 ton of water (found at interval between 50 – 100 ppm) must be sent to the region above the pinch; and 105 ton of water (found at interval between 100 – 400 ppm) be sent to the region below the pinch. This is termed as the water allocation targets in Chapter 4.

The next step in the targeting is to determine the fresh water target at each individual time interval. This is then followed by the storage capacity and wastewater flow targeting. Referring to the water cascade column of Table 5.4, fresh water flow of 185 ton is firstly fed to the first impurity concentration (0 ppm). A water sink in this concentration level (in the first time interval) consumes 20 ton of the fresh water, leaving a flow of 165 ton to the second concentration level, which is then consumed completely by water sinks in this level. Hence we are readily to locate the fresh water consumption in each of these time intervals. Except the water sink in the first time interval, other sinks in time intervals 1.0-5.0 hr (l = 2 - 4) consume a proportional amount of fresh water according to their individual mass flow. These interval-based fresh water flows ($M_{\mathrm{F},\,l}$) is given in the second row of Table 5.5.

The interaction between direct and *indirect water integration* in the network is next determined. Indirect water integration involves the use of water storage system to achieve water reuse and recycle between water-using processes in different time intervals. In order to minimise network complexity and to reduce capital cost, direct water integration is often preferred to indirect water integration. In other words, water sources that exist in each time interval should be integrated with the water sinks before they are sent to water storage tank for future use.

Table 5.5 Identification of interval-based fresh water and wastewater targets, and storage capacity target for Example 5.1 (network with water storage system)

Time interval	***l***	1	2	3	4	**$\Sigma_i M_i - \Sigma_j M_j$ (ton)**	**$M_{C,k}$ (ton)**	**Δm_k (kg)**	**Cum. Δm_k (kg)**
	(hr)	0-1.0	1.0-3.0	3.0-3.5	3.5-5.0				
C_k (ppm)	**$M_{F,l}$** **ΔC_k**	20	100	35	30				
							M_F = 185		
0		-20				-20			
	50						165	8.25	
50			-200	-70	-60	-330			8.25
	50		100	35			-165	-8.25	
100		20	200	50		270			**0 (PINCH)**
	300		20				105	31.50	
400			-20			-20			31.50
	400						85	34.00	
800			20	20	60	100			65.50
	999,200							184852.00	
1,000,000									184917.50
M_{ST} (ton)		0	30	30	0				
$M_{D,l}$ (ton)		20	70	35	60		**M_D = 185**		

Table 5.5 shows the direct water integration that occurs in time interval 1.0-3.5 hr (l = 2 and 3), where water sources at 100 ppm are integrated with water sinks at 50 ppm and 400 ppm (indicated by the hollow arrow and values between concentation levels). Next, the water need in the fourth time interval (3.5-5.0 hr) is fulfilled via indirect water integration. An amount of 30 ton of water at second time interval (1.0-3.0 hr) at 100 ppm is stored for reuse for the water sink in the fourth time interval (indicated by the solid arrow). The cumulative capacity of water storage (M_{ST}) is shown in the second last row of Table 5.5. Since the only water sink that requires indirect water integration is found in the fourth time interval, water storage capacity can be easily determined as 30 ton. This agrees precisely with the previous reported results (Kim and Smith, 2004).

Final procedure in the targeting is to locate the interval-based wastewater flow ($M_{\mathrm{D},\,l}$) in each time interval. All water sources which are not fed to water sinks via direct or indirect integration will leave as the wastewater. This includes part of the sources at 100 ppm and all sources at 800 ppm. The final row of Table 5.5 summarises these interval-based wastewater flows. Note also that a detailed observation reveals that the water flow sent to the region below the global pinch from the pinch-causing streams (at 100 ppm) amounts to 105 ton. This agrees to the water allocation targets identified earlier.

To achieve the various established targets, it is necessary to construct water network for the problem. This will be described in the next section. However, note that through the TDWCA, various network targets (overall and interval-based flows, storage capacity and water allocation targets) are obtained ahead of detailed network design.

5.4 Batch water network design

To achieve the minimum flow targets for a MWR network, network design is to be carried out independently for each time interval. This has been shown in the previous work of batch heat and mass integration (Kemp and Deakin, 1989b; Foo *et al.*, 2005). Note that any appropriate network design tool can be used to construct a water network that features the minimum flow targets, so long as the right targets are correctly identified in the targeting stage. In this thesis, the source sink approach (El-Halwagi, 1997; Vaidyanathan *et al.*1998; Hallale, 2002; Prakash and Shenoy, 2005) has been utilised.

Hallale (2002) pointed out that in order to achieve the water targets, it is necessary to observe the pinch division. For the region above the pinch, the cumulative load surplus is always equal to the cumulative load deficit. This also means that the water sources above the pinch (including fresh water) should neither be fed to the water sinks nor mixed with the water sources below the pinch. These guidelines must be observed during network design in each of the time interval.

After observing the above guidelines, the water network design can be conducted in each of the time intervals using the following equations (El-Halwagi, 1997; Vaidyanathan *et al.*1998; Hallale, 2002; Prakash and Shenoy, 2005):

(a) For water sinks:

Water flow:

$$\sum_i M_{i,j} = M_j \tag{5.1}$$

where $M_{i,j}$ is the mass flow of water fed from water source SR$_i$ to water sink SK$_j$ and M_j is the mass flow of water fed from water sink SK$_j$.

Concentration:

$$\frac{\sum_i M_{i,j} C_i}{\sum_i M_{i,j}} \leq C_j \tag{5.2}$$

where C_i is the impurity concentration for source SR$_i$ and C_j is the limiting concentration for impurity for the water sink SK$_j$.

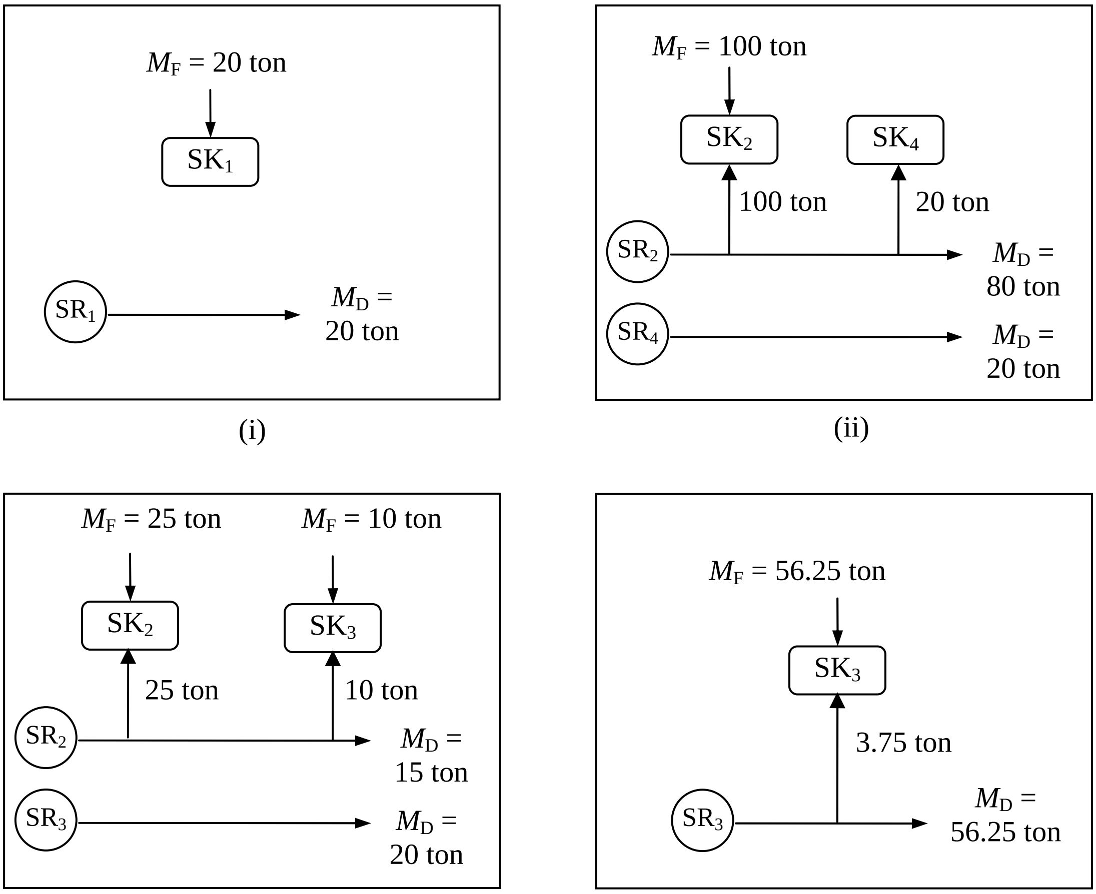
(b) Sources

Water flow:

$$\sum_i M_{i,j} \leq M_i \tag{5.3}$$

where M_i is the total mass flow available from source SR$_i$. Any water from a source that is not fed to a sink will leave as a wastewater stream. Note also that the water flow terms in the above equations are readily transformed into volume terms for case studies where streams are reported in volume measurement.

The MWR network for Example 5.1 is now designed subject to the above-mentioned rules and constraints. Network without water storage system will be considered first. Figure 5.1 shows the network design for all the time intervals involved. Since water sinks and sources exist in all time intervals, direct water integration occurs. Except the water sink in the first time interval (0-1.0 hr) that requires the high quality of fresh water, wastewater generated from the water sources in other time intervals are fed to the water sinks in the same interval. However, due to the impurity limitation of the water sources, only part of the wastewater generated from water source could be reused/recycled. Fresh water is required to supplement the total flow of water required in these time intervals. Total fresh water needed as well as wastewater flows leave the water network amount to 211.25 ton, which agree with the targets established during the targeting stage. Note also that in this MWR network, water fed to each water sink fulfils exactly the required flow in each of the sink, as given by the limiting water data in Table 5.1.



(i) (ii) (iii) (iv)

Figure 5.1 Network design for each time interval in Example 5.1: (a) 0-1.0 hr; (b) 1.0-3.0 hr; (c) 3.0-3.5 hr; (d) 3.5-5.0 hr

Figure 5.2 shows the newly introduced *time-water network diagram* for Example 5.1. As shown, all water-using processes are displayed in terms of their corresponding water sinks and sources, according to the time axis where they exist. The advantage of this time-water network diagram compared to the conventional representation on the continuous water grid diagram is that, designer can now visualise how the water sinks and sources are linked with time. This provides a better visualisation tool in designing an optimum batch water network. Note also that this network representation is also readily to display any non-mass transfer-based processes where water sink and source for a water-using operation may exist in different time intervals.

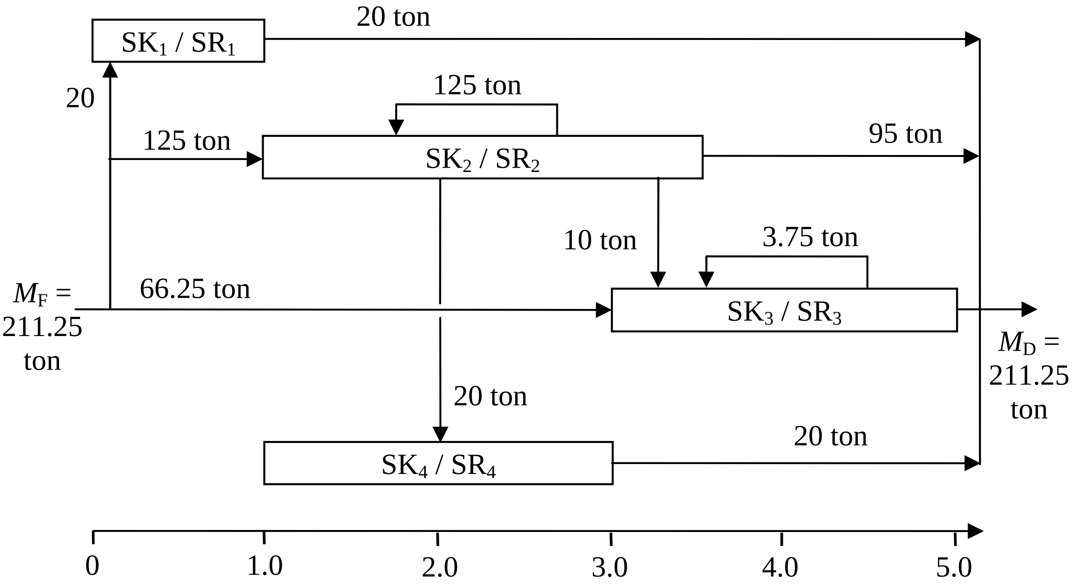


Figure 5.2 Batch water network for Example 5.1 (without water storage system) represented in time-water network

Next, the time-water network diagram is used to depict the network representation on the repeated batch water network with water storage tank system installed. Conceptually, a water storage system may function either as a water source or a water sink, depending on the role of the water storage at the time interval of interest. Water stored at any time interval will function as a source when the stored water is integrated with the water sinks via indirect water integration. On the other hand, the water storage will function as a sink if water is stored at one time interval for further reuse. Figure 5.3 shows the time-water network for this case, which is designed following the various interval-based targets identified during the targeting stage (Table 5.5). The minimum flows achieved in this design, i.e.185 ton of fresh water and wastewater flows agree exactly with the targeted flow using the TDWCA.

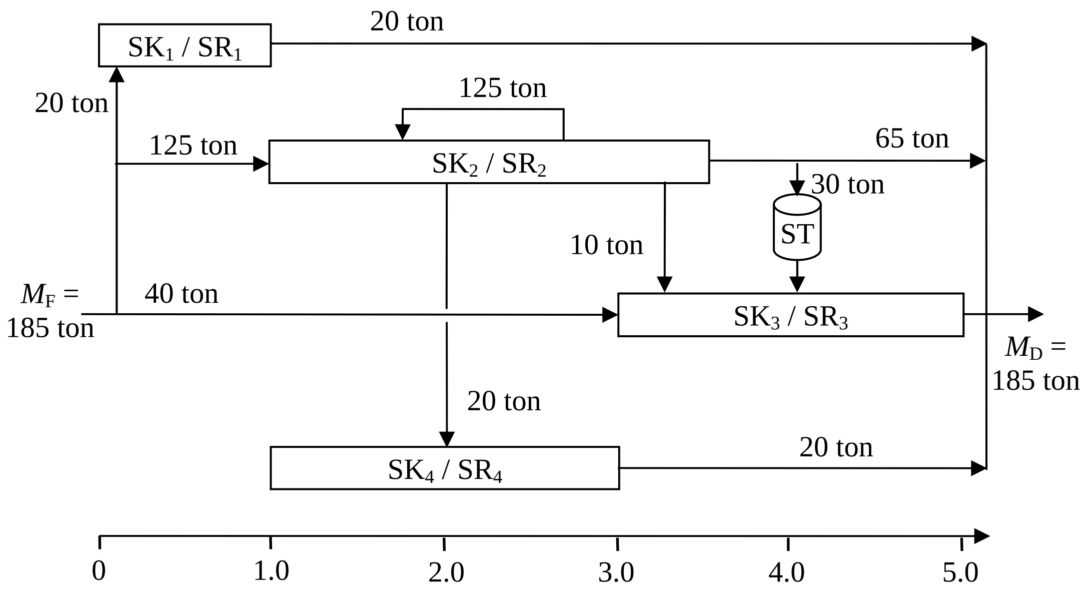


Figure 5.3 Batch water network for Example 5.1 (network with water storage system)

5.5 Example 5.2 - Wang and Smith (1995b)

To demonstrate the versatility of the newly developed approach, a second case study is solved. This is the classical mass transfer-based case study reported by Wang and Smith (1995b) for batch water network. Data for this case study is presented in Table 5.6. This case study comprises of three mass transfer-based water-using operations.

Table 5.6 Limiting water data for Example 5.2 (Wang and Smith, 1995b)

Water sink, SK$_j$	**Flowrate, F_j (ton/h)**	**Concentration, C_j (ppm)**	**Starting time, t^s (h)**	**Ending time, t^t (h)**	**Water flow, M_j (ton)**
SK$_1$	100	100	0.5	1.5	100
SK$_2$	80	0	0	0.5	40
SK$_3$	50	100	0.5	1.0	25

Water sources, SR$_i$	**Flowrate, F_i (ton/h)**	**Concentration, C_i (ppm)**	**Starting time, t^s (h)**	**Ending time, t^t (h)**	**Water flow, M_i (ton)**
SR$_1$	100	400	0.5	1.5	100
SR$_2$	80	200	0	0.5	40
SR$_3$	50	200	0.5	1.0	25

The minimum water targets for repeated batch processes with water storage computed using the time-dependent WCA technique were both calculated as 102.5 ton (Table 5.7). Fresh water and wastewater mass flows for individual time interval as well as storage capacity targeting were also shown in Table 5.7.

Table 5.7 TDWCA for Example 5.2 (network with water storage system)

Time interval	***k***	1	2	3	**$\Sigma_i M_i - \Sigma_j M_j$ (ton)**	**$M_{C,k}$ (ton)**	**Δm_k (kg)**	**Cum. Δm_k (kg)**
	(hr)	0-0.5	0.5-1.0	1.0-1.5				
C_k (ppm)	**$M_{F,l}$** / **ΔC_k**	40	37.5	25				
						M_F = 102.5		
0		-40			-40		6.25	
	100					62.5		6.25
100			-75	-50	-125		-6.25	
	100		25			-62.5		**0**
200		40	25		65		0.50	**(PINCH)**
	200					2.5		0.50
400			50	50	100		102459.00	
	999600							102459.50
1,000,000							6.25	
M_{ST} (ton)		37.5	25	0				
$M_{D,l}$ (ton)		2.5	50	50		**M_D = 102.5**		

Figure 5.4 shows the network design for Example 5.2. As shown in Table 5.7 and Figure 5.4, water flows and the water storage capacity agree precisely with the reported results (Wang and Smith, 1995b; Kim and Smith, 2004).

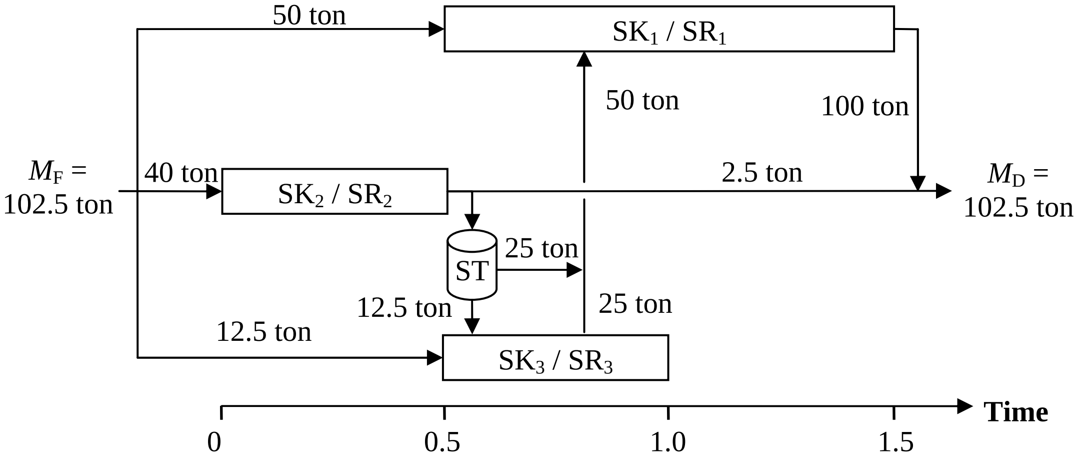


Figure 5.4 Batch network design for Example 5.2

5.6 Conclusion

A two-stage approach to synthesise a batch maximum water recovery (MWR) network has been developed. In the first stage, time-dependent water cascade analysis (TDWCA) technique is used to establish various targets for a batch water network. This includes the overall and interval-based minimum fresh water and wastewater flow targets, water allocation targets as well as the storage capacity target. Once these targets are identified, network design is carried out in each of the time interval. A time-water network diagram is introduced to represent the overall batch water network.

CHAPTER 6

RESULT AND DISCUSSION – GAS CASCADE ANALYSIS

6.1 Introduction

In this chapter, the cascade analysis targeting procedure developed in Chapter 3 will be applied to set the minimum flowrate targets for utility gas networks in a grassroots design. The *gas cascade analysis* (GCA) technique enables quick and accurate identification of the minimum fresh and discharge gas flowrates, pinch point location(s) as well as resource allocation targets for a utility gas network. Multiple pinch problems and appropriate selection of gas purification techniques can be systematically assessed via the GCA. Different industrial processes involve the integration of nitrogen, oxygen and hydrogen gases have been used to prove the applicability of GCA technique in locating the various network targets, prior to detailed design of the utility gas network. The main assumption of this chapter is the exclusion of gas compression in network synthesis.

6.2 Nitrogen integration (Example 6.1)

Figure 6.1 shows the process flow diagram of a magnetic-tape manufacturing process (El-Halwagi, 1997). Coating ingredients are dissolved in an organic solvent and formed a slurry mixture. The slurry is then suspended with resin binders and special additives. Next, the coating slurry is deposited on a base film. Nitrogen gas is used to induce evaporation rate of solvent that is proper for deposition. A small amount of the solvent is decomposed into other organic species in the coating chamber. The decomposed organics are then separated from the coating chamber exhaust gas using a membrane unit. Retentate stream consisting mainly of nitrogen and laden with 1.9 wt/wt% organic solvent leaves the membrane unit at a flowrate of 3.0 kg/s.

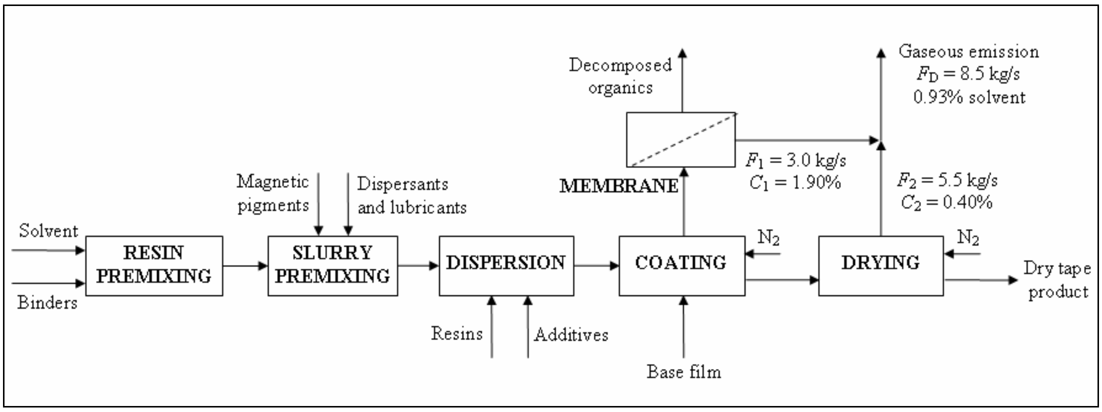


Figure 6.1 Process flow diagram of a magnetic tape manufacturing process (El-Halwagi, 1997)

The coated film undergoes a drying process where nitrogen gas is used to evaporate the remaining solvent. The dryer exhaust gas has a flowrate of 5.5 kg/s and a solvent concentration of 0.4 wt/wt%. The two exhaust gas streams are mixed and disposed off. In order to reduce nitrogen consumption, it is proposed to recycle the solvent-laden exhaust gas to the coating and drying processes, subject to the following constraints (El-Halwagi, 1997):

i. Coating
  - $3.0 \leq$ flowrate of gaseous feed (kg/s) ≤ 3.2
  - $0.0 \leq$ wt% of solvent ≤ 0.2

ii. Drying
  - $5.5 \leq$ flowrate of gaseous feed (kg/s) ≤ 6.0
  - $0.0 \leq$ wt% of solvent ≤ 0.1

It could be assumed that the outlet gas concentration from both the coating and drying processes are independent of the feed gas concentration (El-Halwagi, 1997). The above two constraints require the gaseous flowrate and its solvent concentration in the units to be bounded within the given range. In order to maximise reuse, the maximum permissible inlet concentration and the minimum feed flowrate should be assigned as the *limiting concentration* and *limiting flowrate* for each water demand, respectively (Foo *et al.* 2006). Also, in order to maximise nitrogen reuse, it is necessary to segregate the sources into individual streams since mixing tends to degrade the source streams' qualities. In this case, the solvent laden exhaust gas should be segregated into the individual streams of membrane retentate and dryer exhaust gas. Fresh make-up nitrogen is solvent-free, and hence, has a limiting concentration of 0 wt%. Limiting data for the gas sinks and sources are summarised in Table 6.1.

Table 6.1 Limiting data for Example 6.1 (nitrogen integration)

Gas sinks, SK_j		**Flowrate**	**Concentration**
j	**Stream**	**F_j (kg/s)**	**C_j (ppm)**
1	Drying	5.5	0.1
2	Coating	3.0	0.2
Gas sources, SR_i		**Flowrate**	**Concentration**
i	**Stream**	**F_i (kg/s)**	**C_i (ppm)**
1	Membrane retentate	3.0	1.9
2	Drying	5.5	0.4
	Fresh supply	To be determined	0

6.3 Gas cascade analysis technique

Steps in conducting a GCA is similar to that of water cascade analysis for water network in continuous mode as presented in Chapter 4. The result from GCA for Example 6.1 is presented in the gas cascade table (GCT) in Table 6.2. As shown, the concentration levels (C_k) are arranged in an ascending order in column 1 and the flowrate of each gas sink ($F_{SK,\ j}$) and source ($F_{SR,\ i}$) is located individually at its respective concentration level *k* in columns 3 and 4. The difference between the gas sources and sinks at each concentration level *k* are given in column 5.

Table 6.2 GCT for nitrogen integration (Example 6.1)

Level, k	**C_k (wt/wt%)**	**$\Sigma_j F_j$ (kg/s)**	**$\Sigma_i F_i$ (kg/s)**	**$\Sigma_i F_i - \Sigma_j F_j$ (kg/s)**	**$F_{C,k}$ (kg/s)**	**Δm_k (kg/s)**	**Cum. Δm_k (kg/s)**
					F_F = 5.625		
1	0						
					5.625	0.006	
2	0.1	5.5		-5.5			0.006
					0.125	0.000	
3	0.2	3.0		-3.0			0.006
					-2.875	-0.006	
4	0.4		5.5	5.5			**0** **(PINCH)**
					2.625	0.039	
5	1.9		3.0	3.0			0.039
					F_D = 5.625	562.393	
6	100						562.433

Table 6.2 shows the fresh nitrogen gas feed (F_F) and its discharge flowrate (F_D) in the cumulative flow (F_C) column have both been reduced to 5.625 kg/s. This corresponds to a reduction of 34% from the original feed and discharge flowrates (sum of the individual process flowrates in Table 6.1). Column seven of the GCT in Table 6.2 (Δm) is the impurity load (in this case, solvent load) in each concentration interval, obtained from the product of the cumulative gas flowrate (F_C) and the concentration difference (ΔC). The pinch concentration for the gas network exists at 0.4%, where there is zero cumulative impurity load (Cum. Δm). The pinch limits the gas reuse/recycle in a network. From the limiting data in Table 6.1, emission from the drying process (SR_2) was identified as the pinch-causing source for this example. In order to achieve the minimum gas targets, 2.875 kg/s of SR_2 which exists between intervals k = 3 and k = 4 should be allocated to the region above the pinch while 2.625 kg/s of SR_2 between k = 4 and 5 should be allocated below the pinch. The exact pinch-causing stream distribution to meet the minimum gas targets is termed as the *resource allocation targets*, similar to that of the water allocation targets in Chapters 4 and 5. In the next section, another example involving oxygen reuse and recycle will be presented to illustrate the network design technique to achieve the various network targets established.

6.4 Oxygen integration (Example 6.2)

Some preliminary work on oxygen integration has focused on the optimum reuse of oxygen in wastewater treatment plant (Zhelev and Ntlhakana, 1999; Zhelev and Bhaw, 2000; Zhelev, 2002). The following example is an attempt to explore the interactions and possible site-wide integration between process and utility sections for maximum oxygen recovery.

Figure 6.2 shows a process plant that consumes a large amount of high-purity oxygen in its oxidation processes. Relatively small portion of the oxygen is also fed to enhance the combustion system as well as for the aerobic section of the wastewater treatment plant. The sources of oxygen emitted from the oxygen-consuming processes are still of good quality and should therefore be reused to reduce the fresh oxygen intake.

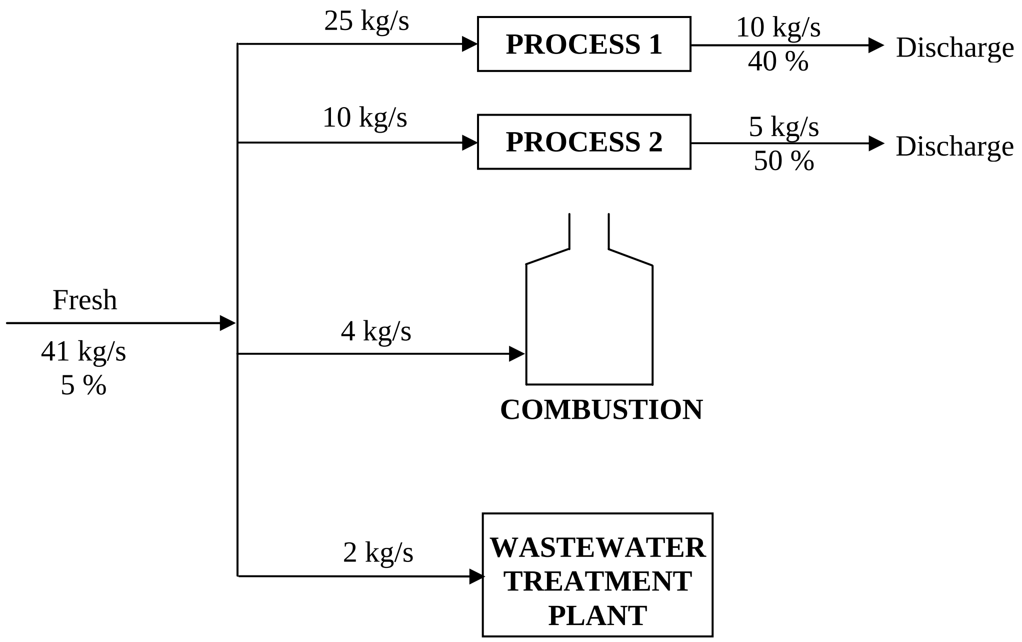


Figure 6.2 Process flow diagram for oxygen integration (Example 6.2)

Limiting data for all oxygen sinks and sources are given in Table 6.3. Note that, since GCA is able to handle impure fresh feeds, the 5% impurity in fresh oxygen supply should not pose any problems in getting accurate minimum gas flowrate targets.

Table 6.3 Limiting data for oxygen integration (Example 6.2)

Gas sinks, SK_j		**Flowrate**	**Concentration**
j	**Stream**	**F_j (kg/s)**	**C_j (wt/wt%)**
1	Process 1	25	10
2	Process 2	10	10
3	Combustion	4	65
4	Wastewater treatment	2	65
Gas sources, SR_i		**Flowrate**	**Concentration**
i	**Stream**	**F_i (kg/s)**	**C_i (wt/wt%)**
1	Process 1	10	40
2	Process 2	5	50
	Fresh supply	To be determined	5

The GCT for this case study (Table 6.4) gives fresh oxygen supply (F_F) and discharge (F_D) targets at 30 kg/s and 4 kg/s respectively. This corresponds to a fresh oxygen reduction of 27% for and discharge gas reduction of 73%, as compared to the base-case system shown in Figure 6.2.

Table 6.4 GCT for Example 6.2

Level, *k*	**C_k (wt/wt%)**	**$\Sigma_j F_j$ (kg/s)**	**$\Sigma_i F_i$ (kg/s)**	**$\Sigma_i F_i - \Sigma_j F_j$ (kg/s)**	**$F_{C,k}$ (kg/s)**	**Δm_k (kg/s)**	**Cum. Δm_k (kg/s)**
					F_F = 30		
1	5			0			
					30	1.50	
2	10	35		-35			1.50
					-5	-1.50	
3	40		10	10			**0.00 (PINCH)**
					5	0.50	
4	50		5	5			0.50
					10	1.50	
5	65	6		6			2.00
					F_D = 4	1.40	
6	100			0			3.40

6.5 Network design

This section briefly reviews the design technique for utility gas network developed by Hallale and Liu (2001). Note that other water network design techniques may also be appropriately adopted (El-Halwagi, 1997; Prakash and

Shenoy, 2005; Almutlaq and El-Halwagi, 2005; Aly *et al.*, 2005). The various network targets established using GCA technique in the previous section serves as a guide for network design.

The pinch concentration identified in the targeting stage plays an important role in the designing a network for maximum gas reuse/recycle. The pinch divides a network into two design regions, i.e. the regions above the pinch and below the pinch, for problems involving a single pinch. It is essential to observe the pinch division in order to achieve the minimum flowrates established during the targeting stage. In the region above the pinch, cumulative impurity load surplus is in mass balance with load deficit. On the other hand, there is always excess impurity load in the region below the pinch. The region above the pinch is therefore controlling the overall gas flowrate balance for the network, and hence, is the most constrained part of the network.

Following the above observation, in designing a gas network, a gas source above the pinch (including the external gas supply) must not be fed to a gas sink below the pinch. Violating this rule will result in higher fresh gas flowrate. This rule also applies during mixing of different gas sources belonging to the different pinch regions. The pinch-causing stream(s) that exist at the pinch concentration is however, an exception to this rule. Recall that, part of the pinch causing stream(s) belong to the region above the pinch, while the remaining belongs to the region below the pinch.

In order to maintain steady-state operation of the gas-consuming processes, we need to maintain a uniform mass flowrate and concentration at the inlet stream of the gas-consuming process. The following guidelines can be used to design the network (Hallale and Liu, 2001):

(a) Gas sinks

Flowrate:

$$\sum_i F_{i,j} = F_j \tag{6.1}$$

where $F_{i,j}$ is the flowrate between source SR_i and sink SK_j.

Gas content:

$$\sum_i F_{i,j} C_i = F_j C_j \tag{6.2}$$

(b) Gas sources

Flowrate

$$\sum_i F_{i,j} = F_i \tag{6.3}$$

Any gas from a source that is not fed to a sink will leave as a discharge stream.

The gas networks for Examples 6.1 and 6.2 designed using the above formulation are shown in Figure 6.3 and 6.4 respectively (assuming sufficient compression available for the gas stream). The flowrate targets as well as the gas allocation targets for the pinch-causing stream identified during the targeting stage are realised here.

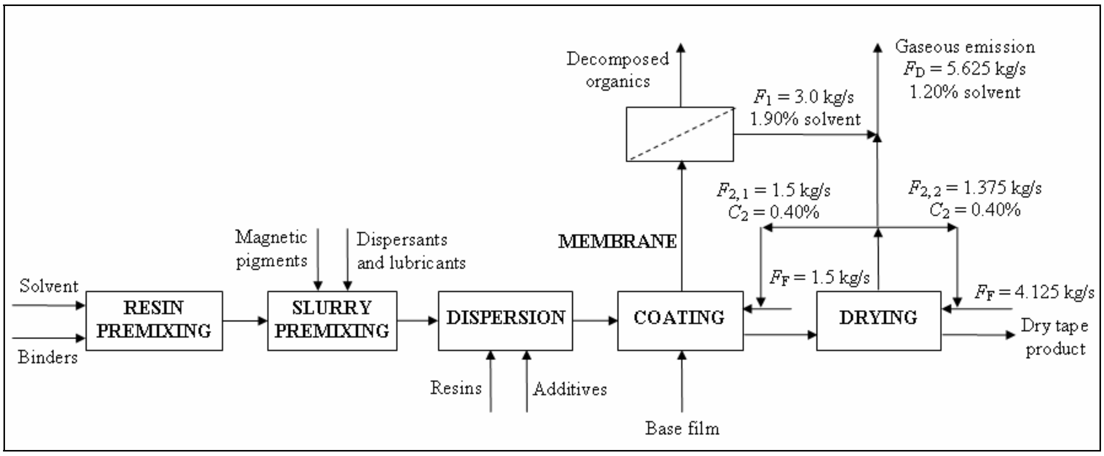


Figure 6.3 Process flow diagram of a magnetic tape manufacturing process (Example 6.1) with exhaust gas reuse and recycling

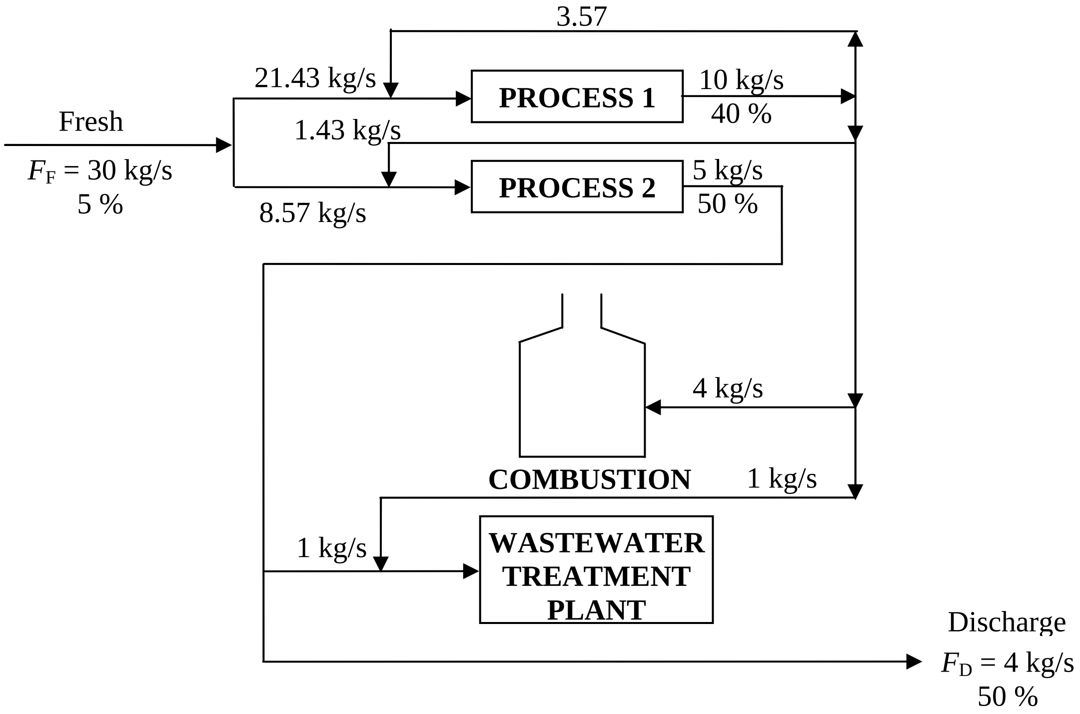


Figure 6.4 Oxygen integration network for Example 6.2

Note that during the design stage, gas network should be designed independently for the individual pinch regions. This is to avoid the gas sources from being fed to the sinks in different thermodynamic regions as well as any inappropriate mixing of gas sources between regions, particularly in a multiple pinch problem. Note also that, many network design options may result as the number of gas sinks and sources increase. A designer can always impose other constraints on network design, such as forbidden or forced connections, due to safety, operation or geographical reasons.

6.6 Hydrogen integration (Example 6.3)

Since hydrogen is a valuable utility gas in crude oil refineries and petrochemical plants, hydrogen reuse and recycle has been the subject of extensive research (e.g. Towler *et al.*, 1996; Hallale and Liu , 2001; Alves and Towler, 2002; Hallale *et al.*, 2002; Bealing and Hutton , 2002a, 2002b; Ricci and Bealing, 2003). Among the most promising graphical tools to set the minimum hydrogen targets are the hydrogen surplus diagram (Alves and Towler, 2002) and the material reuse/recycle pinch diagram (El-Halwagi *et al.*, 2003).

Table 6.5 shows the limiting data for a hydrogen network case study from Alves and Towler (2002), where the existing fresh hydrogen consumption is reported at 277.2 mol/s. There are four hydrogen-consuming processes in this case study which consist of hydrocracker unit (HCU), naphtha hydrotreater (NHT), cracked naphtha hydrotreater (CNHT), and diesel hydrotreater (DHT). There are two hydrogen-producing facilities in this network, i.e. catalytic reforming unit (CRU) and steam reforming unit (SRU). These are the internal hydrogen sources for the network and their use are to be maximised before considering the purchase of hydrogen. A fresh hydrogen supply of having 5% impurity of is available for this case study.

The results of GCA are shown in Table 6.6. The GCT, which is essentially the numerical representation of the hydrogen surplus diagram (Alves and Towler, 2002) avoids the iterative procedure of constructing the surplus diagram. Table 6.6 shows the minimum fresh hydrogen target (F_F) and discharge flowrate (F_F) at 268.8 mol/s and 102.5 mol/s respectively. These values agree with that reported by the graphical targeting tools (Alves and Towler, 2002; El-Halwagi *et al.*, 2003). The GCT identifies the CNHT as the pinch-causing stream, from which 354.9 mol/s must be sent to the region above the pinch and 102.5 mol/s to the region below the pinch.

Table 6.5 Limiting data for hydrogen integration (Example 6.3)

Gas sinks, SK$_j$		**Flowrate**	**Concentration**
j	**Stream**	**F_j (mol/s)**	**C_j (mol%)**
1	HCU	2495.0	19.39
2	NHT	180.2	21.15
3	CNHT	720.7	24.86
4	DHT	554.4	22.43
Gas sources, SR$_i$		**Flowrate**	**Concentration**
i	**Stream**	**F_i (mol/s)**	**C_i (mol%)**
1	HCU	1801.9	25.00
2	NHT	138.6	25.00
3	CNHT	457.4	30.00
4	DHT	346.5	27.00
5	SRU	623.8	7.00
6	CRU	415.8	20.00
	Fresh supply	To be determined	5

Table 6.6 GCT for Example 6.3

Level, k	**C_k (mol%)**	**$\Sigma_j F_j$ (mol/s)**	**$\Sigma_i F_i$ (mol/s)**	**$\Sigma_i F_i - \Sigma_j F_j$ (mol/s)**	**$F_{C,k}$ (mol/s)**	**Δm_k (mol/s)**	**Cum. Δm_k (mol/s)**
					F_F = 268.821		
1	5.00						
					268.821	5.3764	
2	7.00		623.8	623.8			5.3764
					892.621	110.5957	
3	19.39	2495.0		-2495.0			115.9722
					-1602.379	-9.7745	
4	20.00		415.8	415.8			106.1977
					-1186.579	-13.6457	
5	21.15	180.2		-180.2			92.5520
					-1366.779	-17.4948	
6	22.43	554.4		-554.4			75.0572
					-1921.179	-46.6846	
7	24.86	720.7		-720.7			28.3726
					-2641.879	-3.6986	
8	25.00		1940.5	1940.5			24.6739
					-701.379	-14.0276	
9	27.00		346.5	346.5			10.6464
					-354.879	-10.6464	
10	30.00		457.4	457.4			**0.0000**
					F_D = 102.521	71.7647	**(PINCH)**
11	100.00						71.7647

In order to further reduce fresh hydrogen intake, hydrogen sources can be partially treated for reuse and recycle in the hydrogen sinks. The next section demonstrates how GCA can be used to appropriately place a hydrogen purifier in the context of an overall process.

6.7 Appropriate placement of hydrogen purifier

Hallale *et al.* (2002) pointed out that the best option to place a hydrogen purifier is across the pinch. Doing this allows the quality of the hydrogen stream to be upgraded from a region with excess hydrogen (below the pinch) to a region which is tightly constrained in hydrogen (above the pinch). On the other hand, placing the purifier below the pinch will not be beneficial as this amounts to purifying a hydrogen stream only to be discharged from the network. Whilst, purifying a hydrogen stream above the pinch will incur some risks. If the purifier has a low recovery, a large portion of the hydrogen source will end up in the region below the pinch, which leads to less hydrogen in the region above the pinch. Hence, a minimum recovery value is needed to ensure that purification is worthwhile (Hallale *et al.*, 2002).

When dealing with purifier placement, assessment of the impact of changes involves repetitive revisions of the flowrate targets and pinch relocation. Such tasks can be quite cumbersome with the use of graphical tools. The GCA technique that is very amenable to computer programming has managed to overcome this problem.

Given a gas separation membrane with a hydrogen recovery of 95% (Hallale and Liu, 2001), one possible option is to purify the portion of the pinch causing stream (CNHT) which lies below the pinch at 30%, i.e. 102.52 mol/s to a product stream at 2% impurity. From material balance calculations, the flowrate of this high-quality permeate stream is 69.57 mol/s. The flowrate and impurity concentration for the retentate stream is 32.95 mol/s and 89.11% respectively. Adding these two new hydrogen sources at their respective concentration levels yields a new GCT as shown in Table 6.7. Note that the permeate stream from membrane separation at 2% impurity is now much cleaner than the fresh hydrogen supply (5% impurity) and is located at the highest concentration level of the GCT. Hence, the fresh feed and discharge flowrates of the network are now reduced to 196.8 mol/s and 30.475 mol/s respectively. Note also that the pinch concentration increases to the membrane retentate concentration of 89.11 mol%.

Another hydrogen purifier is now assessed. A PSA unit with hydrogen recovery value of 90% and capability to purify the hydrogen stream up to 0.10% impurity (Hallale and Liu, 2001). From material balance calculations, one obtained the product and residue flowrates of 64.65 mol/s and 37.87 mol/s respectively, with the residue stream impurity concentration at 81.05%. Resetting targets using GCA technique gave a reduced fresh hydrogen flowrates of 200 mol/s, which corresponds to a reduced discharge flowrate of 33.711 mol/s. GCT for this option is shown in Table 6.8. Note that in this case, the PSA has also purified the hydrogen source to a higher level relative to the fresh hydrogen supply.

Table 6.7 GCT for Example 6.3 (regeneration with membrane)

Level, k	**C_k (mol%)**	**$\Sigma_j F_j$ (mol/s)**	**$\Sigma_i F_i$ (mol/s)**	**$\Sigma_i F_i - \Sigma_j F_j$ (mol/s)**	**$F_{C,k}$ (mol/s)**	**Δm_k (mol/s)**	**Cum. Δm_k (mol/s)**
1	2.00		69.6	69.6			
			(Permeate)		69.570	208.71	
2	5.00			**F_F = 196.8**			208.71
					266.325	532.65	
3	7.00		623.8	623.8			741.36
					890.125	11028.65	
4	19.39	2495.0		-2495.0			11770.01
					-1604.875	-978.97	
5	20.00		415.8	415.8			10791.03
					-1189.075	-1367.44	
6	21.15	180.2		-180.2			9423.60
					-1369.275	-1752.67	
7	22.43	554.4		-554.4			7670.92
					-1923.675	-4674.53	
8	24.86	720.7		-720.7			2996.39
					-2644.375	-370.21	
9	25.00		1940.5	1940.5			2626.18
					-703.875	-1407.75	
10	27.00		346.5	346.5			1218.43
					-357.375	-1072.13	
11	30.00		354.9	354.9			146.31
					-2.475	-146.31	
12	89.11		33.0	33.0			**0.00**
			(Retentate)		**F_D = 30.475**	331.87	**(PINCH)**
13	100.00						331.87

It can now be concluded that gas separation membrane plays a more important role in reducing the fresh hydrogen target in this hydrogen network, compared to the PSA. This is due to the fact that, membrane with a higher recovery of 95% (as compared to PSA with a recovery of 90%), generate additional amount of hydrogen from the region of excess hydrogen below the pinch, to the region of hydrogen deficit above the pinch. However, one should note that a purifier that gives higher recovery may not necessarily be better. A purifier that produces a product stream at higher purity (e.g. PSA in this case) may sometimes be a better selection in reducing the overall flowrates of the gas network. This situation will be examined in the multiple-pinch problem that follows.

Table 6.8 GCT for Example 6.3 (regeneration with PSA)

Level, k	**C_k (mol%)**	**$\Sigma_j F_j$ (mol/s)**	**$\Sigma_i F_i$ (mol/s)**	**$\Sigma_i F_i - \Sigma_j F_j$ (mol/s)**	**$F_{C,k}$ (mol/s)**	**Δm_k (mol/s)**	**Cum. Δm_k (mol/s)**
1	0.10		64.7	64.7			
			(Product)		64.650	316.785	
2	5.00			**F_F = 200.0**			316.79
					264.641	529.28	
3	7.00		623.8	623.8			846.07
					888.441	11007.79	
4	19.39	2495.0		-2495.0			11853.86
					-1606.559	-980.00	
5	20.00		415.8	415.8			10873.86
					-1190.759	-1369.37	
6	21.15	180.2		-180.2			9504.48
					-1370.959	-1754.83	
7	22.43	554.4		-554.4			7749.66
					-1925.359	-4678.62	
8	24.86	720.7		-720.7			3071.04
					-2646.059	-370.45	
9	25.00		1940.5	1940.5			2700.59
					-705.559	-1411.12	
10	27.00		346.5	346.5			1289.47
					-359.059	-1077.18	
11	30.00		354.9	354.9			212.29
					-4.159	-212.29	
12	81.05		37.9	37.9			**0.00**
			(Residue)		**F_D = 33.711**	638.83	**(PINCH)**
13	100.00						638.83

6.8 Multiple-pinch problems (Example 6.4)

Table 6.9 shows the hydrogen sources and sinks data for Example 6.4. There are six hydrogen sinks and seven hydrogen sources in this hypothetic network. The fresh hydrogen supply in this case has an impurity concentration of 0.10%. Using GCA, the minimum fresh supply and discharge flowrates are found to be 125.21 mol/s and 90.96 mol/s respectively (GCT is shown in Table 6.10). This is a typical multiple-pinch problem. Two pinches are observed in the GCT, i.e. at impurity concentrations of 1.70% and 5.0%. Following the terminology in water network (Chapter 4), the pinch concentration at the lower impurity concentration of 1.70% is designated as the limiting pinch, i.e., the pinch that influences the overall gas flowrates when any process changes take place.

Table 6.9 Hydrogen source and sink data for Example 6.4 (multiple-pinch problem)

Gas sinks, SK$_j$	**Flowrate, F_j (mol/s)**	**Concentration, C_j (mol%)**	**Gas sources, SR$_i$**	**Flowrate, F_i (mol/s)**	**Concentration, C_i (mol%)**
1	120.00	0.10	1	80.00	1.70
2	27.80	1.40	2	75.00	15.00
3	80.00	2.50	3	28.55	4.00
4	60.00	2.50	4	80.00	5.00
5	100.00	3.00	5	120.00	10.00
6	150.00	10.00	6	40.00	1.70
			7	80.00	2.50
			Fresh supply		0.10

In problems involving multiple pinches, more than two thermodynamic regions may exist. For Example 6.4, three distinct thermodynamic regions exist due to the existence of a limiting pinch at 1.70% and a secondary pinch at 5.0%. Utilising the GCA technique, one can quickly identify the pinch-causing stream(s) and the exact hydrogen allocation for the hydrogen source(s) in each of the thermodynamic region. This can then be verified using the network design procedure described previously. One of the possible networks that achieves the various established network targets is shown in Figure 6.5.

Table 6.10 GCT for Example 6.4

Level, k	**C_k (mol%)**	**$\Sigma_j F_j$ (mol/s)**	**$\Sigma_i F_i$ (mol/s)**	**$\Sigma_i F_i - \Sigma_j F_j$ (mol/s)**	**$F_{C,k}$ (mol/s)**	**Δm_k (mol/s)**	**Cum. Δm_k (mol/s)**
					F_F = 125.21		
1	0.10	120		-120			
					5.21	0.068	
2	1.40	27.8		-27.8			0.068
					-22.59	-0.068	
3	1.70		120	120			**0.000**
					97.41	0.779	**(Limiting)**
4	2.50	140	80	-60			0.779
					37.41	0.187	
5	3.00	100		-100			0.966
					-62.59	-0.626	
6	4.00		28.55	28.55			0.340
					-34.04	-0.340	
7	5.00		80	80			**0.000**
					45.96	2.298	**(Secondary)**
8	10.00	150	120	-30			2.298
					15.96	0.798	
9	15.00		75	75			3.096
					F_D = 90.96	77.318	
10	100						80.414

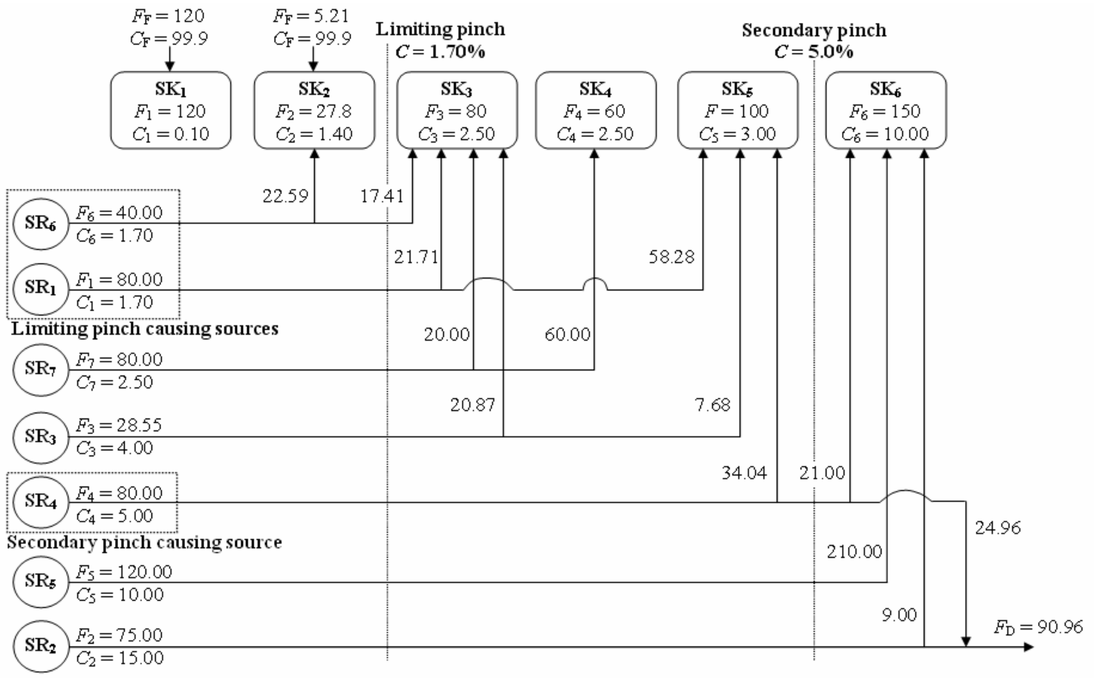


Figure 6.5 One possible network design for Example 6.4: flowrate in mol/s while impurity concentration in mol%

The correct identification of the limiting pinch is crucial in problems involving multiple pinch points and near pinches. Identification of wrong pinch point will result in missed opportunities during hydrogen network debottlenecking. This is particularly important for problems involving multiple pinches, where the region above the limiting pinch is the most constrained part of the network. Debottlenecking strategy will only be beneficial when hydrogen source flowrate is increased above the limiting pinch. Alternatively, decreasing the need of hydrogen sink in the region above the limiting pinch will also achieve the debottlenecking objective. This is another area where quick and accurate determination of the true pinch point and flowrate targets is crucial in gas network analysis. Here, once again, GCA has an important role to play.

Given the same hydrogen purifiers in Example 6.3, the appropriate selection of purifier that will reduce the overall hydrogen flowrates of the network can now be determined. GCT for purifying the hydrogen source using a gas separation membrane (hydrogen recovery of 95% and produces a permeate stream with 2% impurity) is shown in Table 6.11. Note that, though the secondary pinch at 5.0% has been removed, the minimum flowrate targets for this option are the same as before regeneration (Table 6.10). In other words, no benefit is obtained by adding a new membrane separation unit into the network. This is due to the fact that the overall hydrogen flowrate targets is controlled by the most constrained part of the network, i.e. the region above the limiting pinch. Hence the purified product stream must achieve an impurity concentration lower than the limiting pinch concentration before fresh hydrogen requirement can be reduced.

Table 6.11 GCT for Example 6.4 (regeneration with membrane)

Level, *k*	**C_k (mol%)**	**$\Sigma_j F_j$ (mol/s)**	**$\Sigma_i F_i$ (mol/s)**	**$\Sigma_i F_i - \Sigma_j F_j$ (mol/s)**	**$F_{C,k}$ (mol/s)**	**Δm_k (mol/s)**	**Cum. Δm_k (mol/s)**
					F_F = 125.21		
1	0.10	120.00		-120			
					5.21	0.068	
2	1.40	27.80		-27.8			0.068
					-22.59	-0.068	
3	1.70		120.00	120			**0.000**
					97.41	0.292	**(PINCH)**
4	2.00		104.69	104.7			0.292
			(Permeate)		202.11	1.011	
5	2.50	140.00	80.00	-60			1.303
					142.11	0.711	
6	3.00	100.00		-100			2.013
					42.11	0.421	
7	4.00		28.55	28.5			2.434
					70.66	0.707	
8	5.00		80.00	80			3.141
					150.66	7.533	
9	10.00	150.00		-150			10.674
					0.66	0.033	
10	15.00		75.00	75			10.707
					75.66	37.616	
11	64.72		15.31	15.3			48.323
			(Retentate)		**F_D = 90.96**	32.092	
12	100						80.414

Another hydrogen purifier in Example 3 that was used for evaluation was the PSA unit with a hydrogen recovery of 90%, a resulting residue stream at 52.43% purity and a product stream containing 0.10% impurity which was lower than the limiting pinch. Resetting targets using GCA gave a reduced fresh hydrogen target of 54.23 mol/s, and discharge target of 19.98 mol/s (Table 6.12). Due to the reallocation of hydrogen sources within the whole network, the original limiting and secondary pinch disappeared, while a new pinch emerged at the residue stream concentration of 52.43%. Hence, we can conclude that PSA plays a more important role in reducing the overall hydrogen targets in this network, as compared to gas separation membrane. By purifying hydrogen source in the region of excess hydrogen (below the secondary pinch), PSA supplies an extra amount of hydrogen to the region of hydrogen deficit (above the limiting pinch). Finally, note also that all preliminary screening for appropriate placement of hydrogen purifier is carried out prior to the detailed design of the network.

Table 6.12 GCT for Example 6.4 (regeneration with PSA)

Level, *k*	**C_k (mol%)**	**$\Sigma_j F_j$ (mol/s)**	**$\Sigma_i F_i$ (mol/s)**	**$\Sigma_i F_i - \Sigma_j F_j$ (mol/s)**	**$F_{C,k}$ (mol/s)**	**Δm_k (mol/s)**	**Cum. Δm_k (mol/s)**
					F_D = 54.23		
1	0.10	120.00	97.30	-22.70			
			(Product)		31.53	0.410	
2	1.40	27.80		-27.80			0.410
					3.73	0.011	
3	1.70		120.00	120.00			0.421
					123.73	0.990	
4	2.50	140.00	80.00	-60.00			1.411
					63.73	0.319	
5	3.00	100.00		-100.00			1.730
					-36.27	-0.363	
6	4.00		28.55	28.55			1.367
					-7.72	-0.077	
7	5.00		80.00	80.00			1.290
					72.28	3.614	
8	10.00	150.00		-150.00			4.904
					-77.72	-3.886	
9	15.00		75.00	75.00			1.018
					-2.72	-1.018	
10	52.43		22.70	22.70			**0.000**
			(Residue)		**F_D = 19.98**	9.506	**(PINCH)**
11	100						9.506

6.9 Conclusion

The cascade analysis technique has been applied in the synthesis of utility gas networks. Gas cascade analysis (GCA) enables quick and accurate identification of the minimum flowrate targets, pinch point location(s) as well as resource allocation targets for a utility gas network. Appropriate selection of gas purification techniques can be systematically assessed using the GCA. Problems involving multiple pinches can now be handled more efficiently, accurately and with much less effort.

CHAPTER 7

RESULT AND DISCUSSION – PROPERTY CASCADE ANALYSIS

7.1 Introduction

In this chapter, a new graphical tool called the property surplus diagram and cascade analysis targeting procedure are used to determine the minimum resource flowrates in a property-based network for grassroots design. Property surplus diagram is firstly used to provide a basic framework for determining rigorous targets for minimum fresh usage, maximum recycle, and minimum waste discharge. The *property cascade analysis* (PCA) technique is next established to set targets via a tabular approach. PCA eliminates the iterative steps typically associated with a graphical approach. Along with the minimum fresh and waste targets, the material allocation target is another key feature of the PCA. Two case studies are solved to illustrate the applicability of the developed procedures in network of single property.

7.2 Metal degreasing process (Example 7.1)

Figure 7.1 shows a metal degreasing process taken from Kazantzi and El-Halwagi (2005) that will be used to demonstrate how the conventional pinch-based approach can be applied to the synthesis of a property-based network. Currently, a fresh organic solvent is used in the degreaser of a reactive thermal degreasing process to decompose the grease and its organic additives. The solvent is then regenerated for reuse in the degreaser. Fresh solvent is also used in an absorber to capture light gases that escape from the solvent regeneration unit before its gaseous overhead is sent to flare. It was proposed to reuse and recycle part of the solvent that is currently discharged from the process to reduce the present high consumption of fresh solvent.

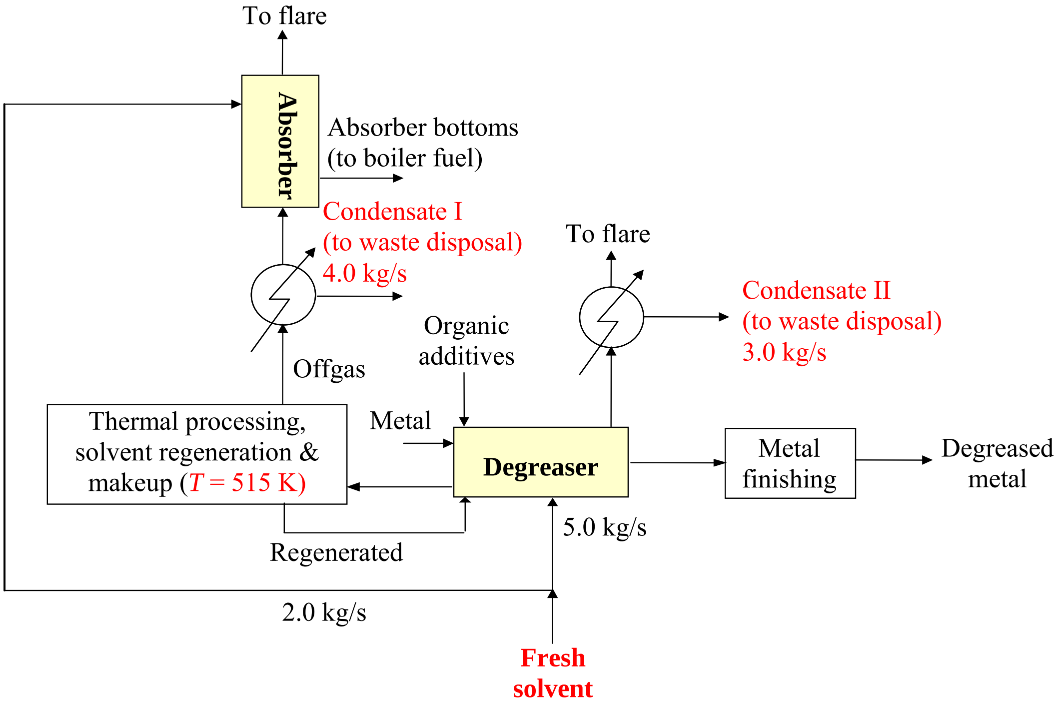


Figure 7.1 Metal degreasing process (Kazantzi and El-Halwagi, 2005)

The main property of the solvent that is considered in evaluating its reuse and recycle, is the Reid Vapour Pressure (RVP), which is important in characterising the volatility, makeup and regeneration of the solvent. Although this can be viewed as a material reuse/recycle problem, the conventional mass integration techniques (e.g. El-Halwagi, 1997; Dunn and El-Halwagi, 2003) could not be applied here since the targeted property, i.e. RVP, is not adequately addressed in terms of concentration. One way to resolve this problem is by employing property integration techniques.

The first step in synthesising a property-based network is to identify the solvent sources and sinks, as well as their associated property data. From Figure 7.1, it is observed that the process produces two condensate streams: Condensate I (Source 1, denoted as SR_1) from the solvent regeneration unit and Condensate II (denoted as SR_2) from the degreaser. The two streams are currently sent to hazardous waste disposal. Since these two streams possess many desirable properties, it is advisable their in-plant reuse/recycle to be considered in order to reduce the fresh solvent consumption of the process. Both the degreaser (as Sink 1, denoted as SK_1) and the absorber (denoted as SK_2) can receive recycled solvent from the process, and hence can be designated as process sinks. Data for the solvent sinks and sources are given in the first four columns of Table 7.1. Note that the two process sinks (degreaser and absorber) impose constraints on the quality of the solvent to be recycled to these units.

Table 7.1 Data for Example 7.1

Process	**Flowrate (kg/s)**	**RVP (atm)**		**Operator ψ(atm$^{1.44}$)**	
		Lower bound	**Upper bound**	**Lower bound**	**Upper bound**
(Sink)					
Degreaser (SK_1)	5.0	2.0	3.0	2.713	4.865
Absorber (SK_2)	2.0	2.0	4.0	2.713	7.362
(Source)					
Condensate I (SR_1)	4.0	6.0		13.199	
Condensate II (SR_2)	3.0	2.5		3.741	
Fresh solvent	To be determined	2.0		2.713	

Next, the raw property values of all solvent sinks and sources are transformed into its associated operator values. The mixing rule for RVP is given below (Kazantzi and El-Halwagi 2004):

$$\overline{\mathrm{RVP}}^{1.44} = \sum_i x_i \mathrm{RVP}_i^{1.44} \tag{7.1}$$

From Eq 2.6 to Eq 2.9 in Chapter 2, the operator for RVP, ψ(RVP), can be expressed as follows:

$$\psi(\mathrm{RVP}_i) = \mathrm{RVP}_i^{1.44} \tag{7.2}$$

Hence, the RVP values of all the solvent sinks and sources are transformed to the corresponding operator values, given in the final two columns of Table 7.1.

In Table 7.1, it can be observed that the fresh solvent has a relatively low operator value compare to that of the two process sources (SR_1 and SR_2). In order to achieve the maximum resource recovery (MRR) objective, the reuse of process solvent sources is to be maximised before the utilisation of the fresh solvent. Hence, the upper bound of the operator value in Table 7.1 is assigned to be the limiting value for the process sink. These limiting operators multiplied by the sink flowrates will then define the *limiting property loads* of the sinks, following Eq. 2.11b. The limiting load indicates the maximum acceptable property load for a given sink. On the other hand, one can also define the property load contained in the solvent sources using Eq. 2.11a. The limiting data for all solvent sinks and sources of the metal degreasing process is shown in Table 7.2. After identifying the property sources and sinks, along with their relevant limiting data, the minimum resource targets will be established using the new targeting techniques described in the following sections.

Table 7.2 Limiting data for Example 7.1

Process	**Flowrate, F (kg/s)**	**Operator, Ψ ($atm^{1.44}$)**	**Load, Δm ($kg.atm^{1.44}/s$)**
(Sinks)			
Degreaser (SK_1)	5.0	4.865	24.323
Absorber (SK_2)	2.0	7.362	14.723
(Source)			
Condensate I (SR_1)	4.0	13.199	52.796
Condensate II (SR_2)	3.0	3.741	11.224
Fresh Solvent	To be determined	2.713	

7.3 The concept of material surplus

In this section, a new graphical tool called the property surplus diagram is developed to provide a fundamental understanding of material flow in a property-based network. This serves as the basis for the cascade analysis targeting technique that will be discussed in the next section.

The property surplus diagram is based on the concept of material surplus that was firstly introduced by Alves and Towler (2002) for the analysis of an integrated refinery hydrogen network. Prior to detailed network design, the hydrogen surplus diagram identifies the minimum fresh hydrogen feed and waste stream targets in a hydrogen network. Later, Hallale (2002) extended this targeting tool into water network, where the water surplus diagram is used to target the minimum fresh water consumption and minimum wastewater generation. Both the aforementioned surplus diagrams are built on the concept of the grand composite curves in heat integration (Linnhoff *et al.*, 1984). This material surplus concept is now extended to property-based network. Obviously, the property surplus diagram provides the same information as the surplus diagrams in hydrogen (Alves and Towler, 2002) and water (Hallale, 2002) networks, as well as the grand composite curves in heat integration (Linnhoff *et al.*, 1984).

In order to generate the property surplus diagram, another plot called the *material sink and source composite diagrams* is needed. These composite plots have also been utilised in hydrogen (Figure 2.15; Alves and Towler, 2002) and water network analysis (Figure 2.6; Hallale, 2002). However, instead of the concentration values in the hydrogen and water networks, the property operator values are now plotted versus their corresponding flowrates of each process sink and source. Utilising the limiting data in Table 7.2, the material sink and source composite plots for Example 7.1 are shown in Figure 7.2. Note that, the flowrate of the fresh solvent has first been set to zero. This value will be re-examined in a later targeting stage.

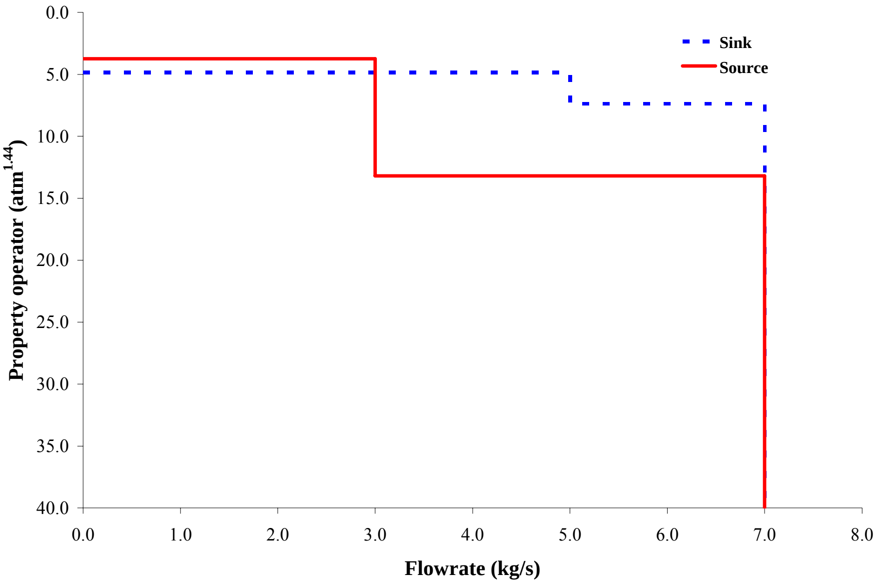
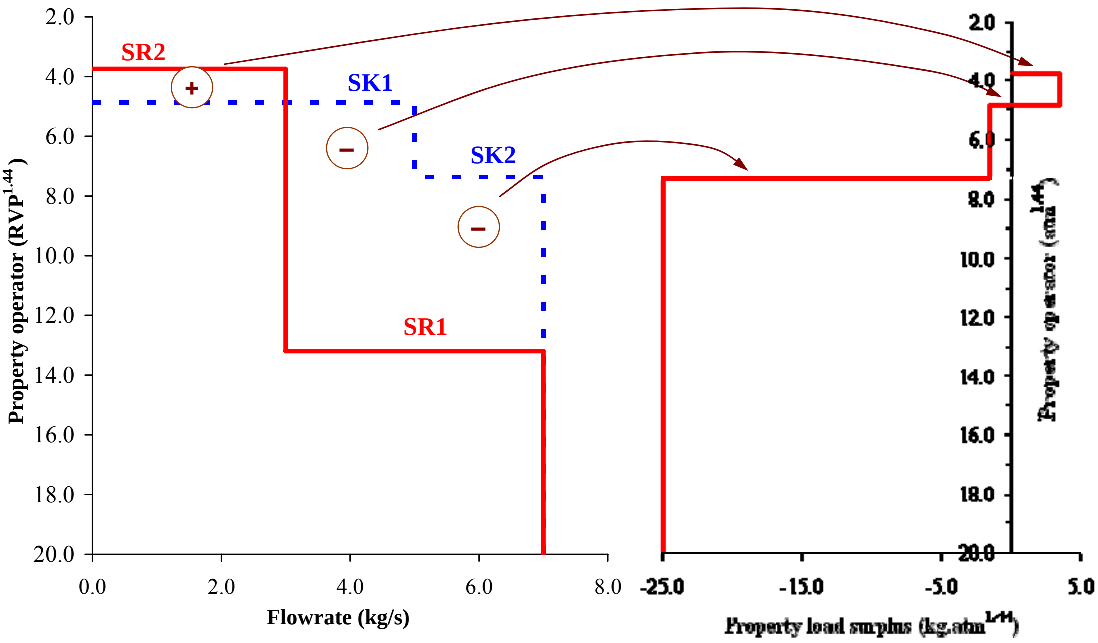


Figure 7.2 Sink and source composite plots for Example 7.1, with the solvent flowrate set to 0 kg/s

Two objectives need to be fulfilled in synthesising a MRR network are the flowrate and the property load requirements of all process sinks. The total flowrate fed from the process sources need to be ensured to satisfy both these criteria for all process sinks in the network. The first criterion, i.e. flowrate feasibility, is easy to inspect from the composite curves. One has to make sure that the total flowrate of the sources is larger than or equal to the total feed flowrate that the sinks require. The composite plots can provide a clear indication if this requirement is satisfied. As long as the source composite extends to the right or touches on the sink composite, this requirement has been fulfilled (Hallale, 2002). From Figure 7.2, it is evidence that, without feeding fresh solvent to the network, process sources are capable of fulfilling the flowrate requirement of the process sinks. A careful observation would indicate that the total flowrate of the sources equals the total flowrate required by the sinks implying that this is a zero discharge process. However, this claim is only valid, once the second feasibility criterion of the network, i.e. the property load feasibility, is also fulfilled.

To fulfil the second feasibility criterion, a newly developed graphical tool called the property surplus diagram is needed. To construct this plot, information from both the sink and source composite plots is needed. In Figure 7.2, the area below the sink composite plot, which is the product between the total sink flowrate and its associated operators, gives the total limiting property load that is acceptable by all process sinks. Similarly, the area below the source composite plot gives the total available property load possessed by the sources. Hence, the area between these composite plots indicates the area where property load is in excess (surplus) or in shortage (deficit) at its associated operator level. Hence, when a source composite lies above the sink composite, the area between the two composite plots indicates a property load surplus for this region. One the other hand, a sink composite lying above a source composite indicates a property load deficit (Figure 7.3a). The operator values (levels) are next plotted against their associated cumulative values of these property load surplus or deficit to form the *property surplus diagram*, as shown in Figure 7.3(b). Note that, since the cumulative value of the property load is plotted, a surplus load causes the surplus diagram to move to the right; while a deficit load moves it to the left.



(a) (b)

Figure 7.3 Construction of a property surplus diagram: (a) Sink and source composite plots; (b) Property surplus diagram

A complete property surplus diagram with the assumed 0 kg/s fresh solvent feed is shown in Figure 7.3(b). Notice that part of this plot lies in the negative region of the property load surplus axis (*x*-axis), and this indicates that property load infeasibility occurs in this property range. This happens because the property load supplied by the sources is not sufficient to meet the load requirements of the sinks without the use of fresh solvent. Hence, the assumed zero fresh solvent flowrate does not fulfil the second feasibility criterion for the network synthesis. In order words, fresh solvent is needed to fulfil the second feasibility criterion and to restore the network feasibility. Hence, the aforementioned procedure of developing composite curves and surplus diagrams has to be repeated until the surplus diagram touches the property operator axis (*y*-axis), and no part of the surplus diagram lies in the negative region

Considering that the objective for network synthesis is to minimise the resource targets (minimum fresh solvent feed and waste discharge), the minimum amount of fresh solvent flowrate that yields the minimum waste for the network need to be determined. However, similar to the situation in hydrogen and water network synthesis problems (Alves and Towler, 2002; Hallale, 2002), the determination of minimum fresh solvent feed through the surplus diagram involves a tedious and time consuming trial-an-error solution. In addition, the surplus diagram suffers from its limitation of generating highly accurate targets due to its graphical nature. In view of the above shortcoming in the property surplus diagram, PCA is presented to locate the minimum resource targets. This is discussed in the following section.

7.4 Property cascade analysis technique

Steps in conducting a PCA is similar to that of water cascade analysis (WCA) or gas cascade analysis (GCA) techniques in Chapter 4 and 6, with impurity concentration changed to property operator. The result from PCA for Example 7.1 is presented in the property cascade table (PCT) in Table 7.3.

Table 7.3 PCT for metal degreasing process (Example 7.1)

Level, *k*	**ψ_k (atm$^{1.44}$)**	**$\Sigma_j F_j$ (kg/s)**	**$\Sigma_i F_i$ (kg/s)**	**$\Sigma_i F_i - \Sigma_j F_j$ (kg/s)**	**$F_{C,k}$ (kg/s)**	**Δm_k (kg.atm$^{1.44}$/s)**	**Cum. Δm_k (kg.atm$^{1.44}$/s)**
					$F_F = 2.38$		
1	2.713			0			
					2.38	2.45	
2	3.741		3.0	3.0			2.45
					5.38	6.05	
3	4.865	5.0		-5.0			8.49
					0.38	0.95	
4	7.362	2.0		-2.0			9.45
					-1.62	-9.45	
5	13.199		4.0	4.0			**0**
					$F_D = 2.38$	16.20	**(PINCH)**
6	20.000						16.20

Table 7.3 shows both the minimum fresh solvent (F_F) and discharge (F_D) flowrates of 2.38 kg/s for Example 7.1, match the targets identified using the graphical pinch diagram of Kazantzi & El-Halwagi (2005). By plotting the cumulative loads at each operator level, a feasible property surplus diagram is created in Figure 7.4. Notice that the entire surplus diagram is now shifted to the positive region of the property load surplus axis (x-axis).

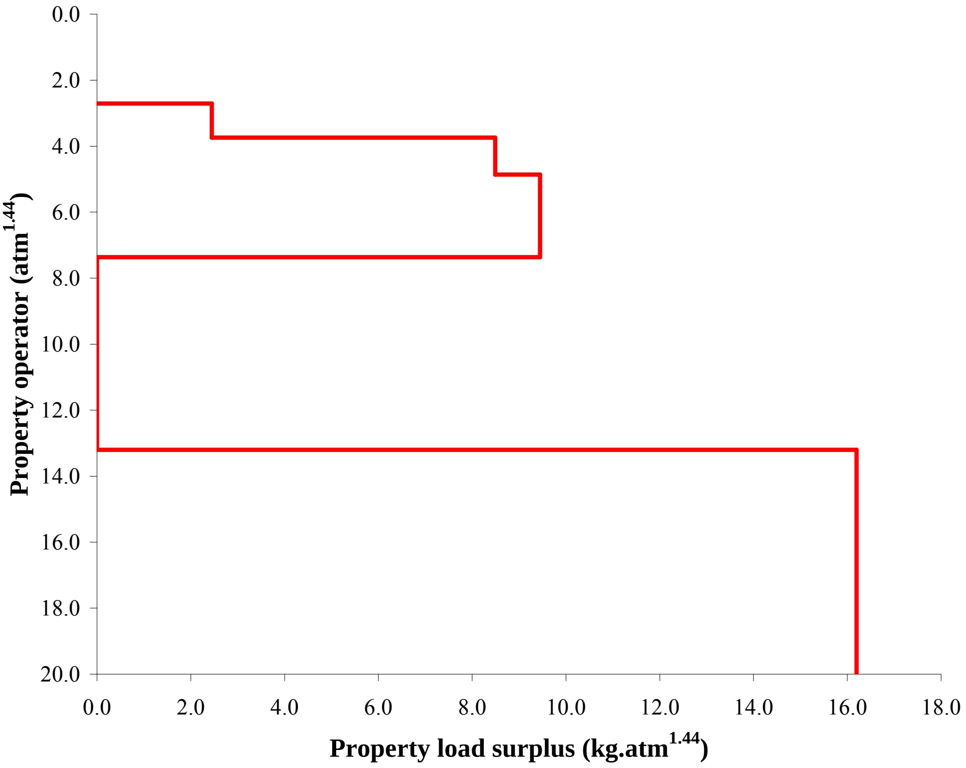


Figure 7.4 A feasible property surplus diagram for Example 7.1

Process Condensate I (SR_1) with a flowrate of 4.0 kg/s is identified as the pinch-causing source for this example. In order to achieve the minimum resource targets, 1.62 kg/s of solvent source SR_1 (found at the interval between ψ_4 and ψ_5) is sent to the region above the pinch, while 2.38 kg/s (found below ψ_5) is sent to the region below the pinch, which eventually becomes the discharge stream (F_D).

A "balanced" material sink and source composite diagram constructed using the targeted fresh solvent flowrate (Figure 7.5) can be used to summarise the above-mentioned insight. As shown, the purest segment of the source composite curve in Figure 7.5 represents the fresh solvent feed of 2.38 kg/s. The pinch operator found previously divides the network into two thermodynamic regions, i.e. one above the pinch and the other below the pinch. Also, Figure 7.5 shows that, the pinch-causing source (at the lowest operator level among all sources) has its exact allocation flowrates for network above and below the pinch, as have been targeted earlier. These exact material allocation flowrates can also be verified with the detailed network design technique, which will be discussed in the next section.

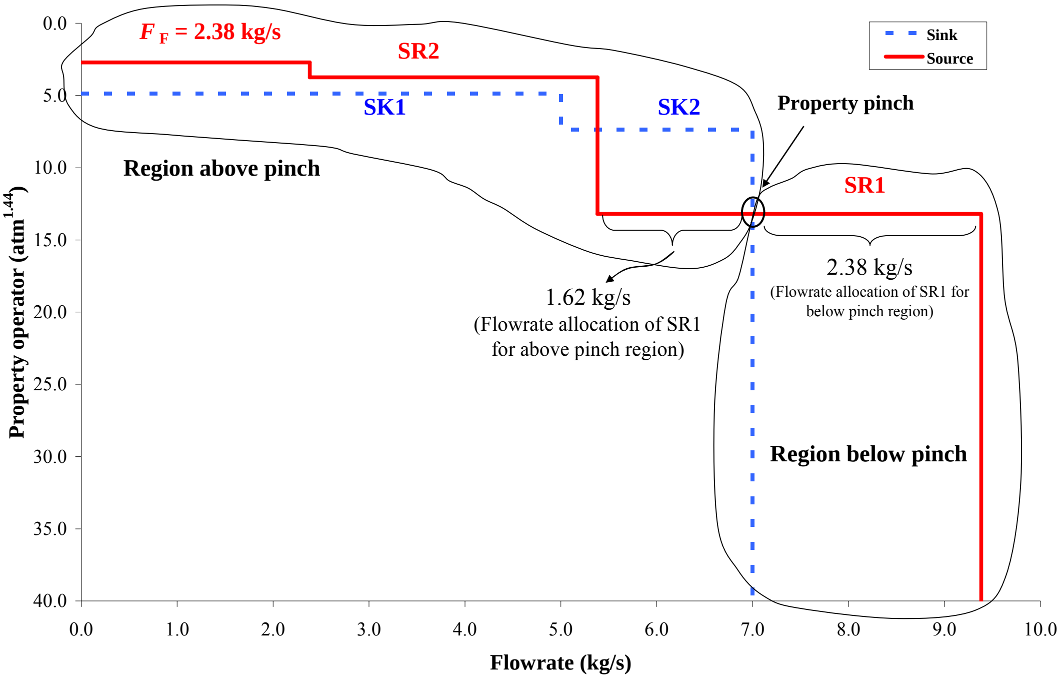


Figure 7.5 Balanced material sink and source composite diagram for Example 7.1

7.5 Property-based network design

This section discusses a simple technique for synthesising a property-based network that achieves the resource targets previously established. Example 7.1 will be used to illustrate the design procedure.

The pinch operator found previously divides the network into two thermodynamic regions, i.e. one above the pinch and the other below the pinch. Observing the pinch division is essential in achieving the minimum resource targets determined during the targeting stage. This observation implies that one should not feed a source located above the pinch (including the fresh resource) to a sink below the pinch in designing a property-based network. Violating this rule will incur a higher resource penalty. This guideline also holds for mixing process sources from different thermodynamic regions. However, an exception to this rule is for stream(s) found at the pinch operator (SR_1 in Example 7.1), since these stream(s) belong to both regions.

After observing the above guidelines, a property-based network can be designed using the following equations, which were originally developed for mass exchange network design (El-Halwagi, 1997):

(a) For sinks

Flowrate:

$$\sum_{i} F_{i,j} = F_{j} \tag{7.3}$$

where $F_{i,j}$ is the flowrate fed from source i to sink j.

Property load:

$$\sum_{i} \Delta m_{i,j} \leq \Delta m_{j}^{\max} \tag{7.4}$$

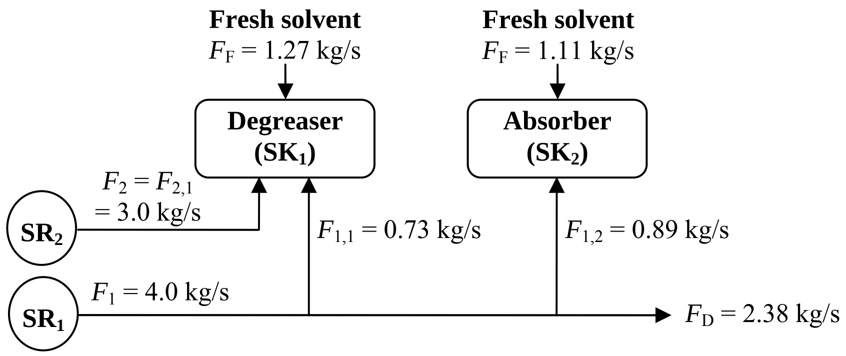
where $\Delta m_{i,j}$ is the property load fed from source i to sink j, that is given as the product of $F_{i,j}$ and ψ_i.

(b) For sources

Flowrate:

$$\sum_{i} F_{i,j} \leq F_{i} \tag{7.5}$$

Eq 7.3 and 7.4 provide expressions for a fixed flowrate and the maximum acceptable property load required by a sink, respectively; whereas Eq 7.5 indicates that the flowrate fed from source i to sink j is bounded within its available limit. The remaining portion of the source that is not fed to a sink will leave as a waste stream. One possible network for Example 7.1 using the above formulation is shown in Figure 7.6, where SR_1 (Condensate I) is reused in both sinks while SR_2 (Condensate II) in sink SK_1 (Degreaser) alone. For cases involving more sources and sinks, many alternative design options are possible. One may also impose other constraints into the network design, e.g. forbidden matches for safety or operability reasons. For cases where process sinks appear in different regions network design is best conducted independently for each thermodynamic region so as to prevent the sources from different thermodynamic regions to be fed to the sinks and to avoid unnecessary mixing of sources across these regions. This is particularly important in multiple pinch problems where more thermodynamic regions exist in a network.



Sinks	Sources	$F_{i,j}$	x_i	RVP	$\Psi_{i,j}$	$x_i \Psi_{i,j}$	$\Delta m_{i,j}$
SK_1	Fresh	1.27	0.254	2.0	2.713	0.689	3.446
	SR_2	3.00	0.600	2.5	3.741	2.245	11.224
	SR_1	0.73	0.146	6.0	13.199	1.927	9.635
	TOTAL	**5.0**	**1.0**			**4.861**	**24.305**
SK_2	Fresh	1.11	0.557	2.0	2.713	1.510	3.021
	SR_1	0.89	0.443	6.0	13.199	5.851	11.702
	TOTAL	**2.0**	**1.0**			**7.362**	**14.723**

Figure 7.6 Network design for Example 7.1

Figure 7.7 shows the final configuration of the degreaser plant in Example 7.1. A fresh solvent supply at 2.38 kg/s is fed to the process, while the same amount of waste solvent is discharged from the process.

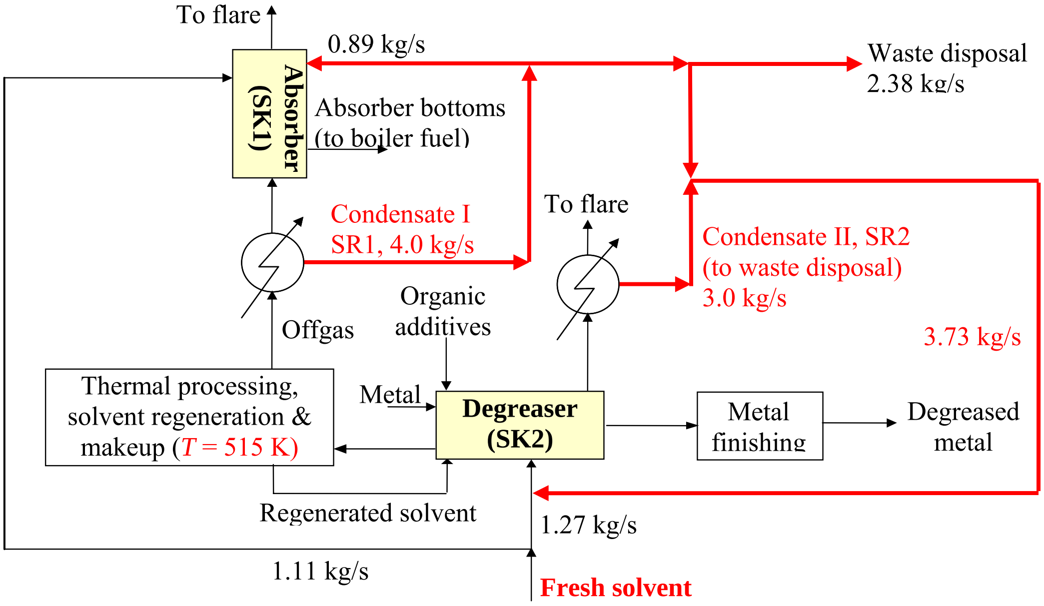


Figure 7.7 Network design for degreaser plant to achieve MRR objective (before process modification)

7.6 Process modifications

Making appropriate changes to a process has been widely accepted as an effective measure to further reduce resource targets in mass integration (e.g., El-Halwagi, 1997; Noureldin and El-Halwagi, 1999). The same measure can be applied for property integration. This will be again demonstrated using Example 7.1.

The configuration of the degreaser plant after solvent reuse/recycle is shown in Figure 7.7. It is now desirable to further reduce the fresh solvent consumption by making changes in the process. It is also observed that the total flowrate of the process sources, i.e. SR_1 and SR_2 is equal to the total flowrate requirements of the sinks (SK_1 and SK_2). To achieve zero discharge, one possible option is to modify the property of SR_1 (since this is the only source that is currently discharged from the process), so that it can be reused further in both process sinks.

To fulfil the flowrate requirements of both sinks, 2.0 kg/s of solvent from SR_1 is to be fed to each of these sinks. Since the degreaser has already been fed with the entire SR_2 (with a flowrate of 3.0 kg/s) it is not necessary to make any changes in this solvent source. However, for any attempt to reuse more solvent from SR_1, we will have to take into consideration the maximum property load constraint of the sinks as imposed by Eq. 2.12. Eq. 7.6 shows that the RVP for Condensate I, RVP_{SR1}, is a function of the operating temperature in the solvent regeneration unit (Kazantzi and El-Halwagi, 2004):

$$\mathrm{RVP}_{\mathrm{SR1}} = 0.56e^{\left(\frac{T-100}{175}\right)} \tag{7.6}$$

where T is the temperature of the thermal processing system in Kelvin (K). The acceptable range of this temperature is between 430 and 520 K. At present, the thermal processing system operates at 515 K, leading to an RVP of 6.0 atm. This operating condition can be modified to enable more solvent from SR_1 to be reused in the sinks.

Analysis of the property load currently received by the process sinks in Figure 7.7 indicates that both sinks are currently receiving property loads at their maximum acceptable level, i.e. 24.323 kg.atm$^{1.44}$/s and 14.723 kg.atm$^{1.44}$/s respectively. In this regard, the degreaser receives 9.659 kg.atm$^{1.44}$/s from SR$_1$, 11.223 kg.atm$^{1.44}$/s from SR$_2$ and the remaining 3.440 kg.atm$^{1.44}$/s load from the fresh solvent. In addition, the absorber receives a load of 11.702 kg.atm$^{1.44}$/s from SR$_1$ and 3.011 kg.atm$^{1.44}$/s from the fresh solvent. Hence, to entirely substitute the current fresh solvent with SR$_1$, one should not feed more than 13.099 kg.atm$^{1.44}$/s of property load to the degreaser (recalling that a load of 11.223 kg.atm$^{1.44}$/s is currently fed from SR$_1$) and 14.723 kg.atm$^{1.44}$/s of property load to the absorber. Based on these constraints, one can back calculate the maximum acceptable property operator for the degreaser and the absorber at 6.55 atm$^{1.44}$ and 7.36 atm$^{1.44}$ respectively. A lower value is chosen in this case in order to satisfy both sinks. From Eq. 7.6, this corresponds to an operating temperature of 430 K, which lies within the acceptable range of temperatures for the solvent regeneration unit. The final flowsheet after process modification is shown in Figure 7.8.

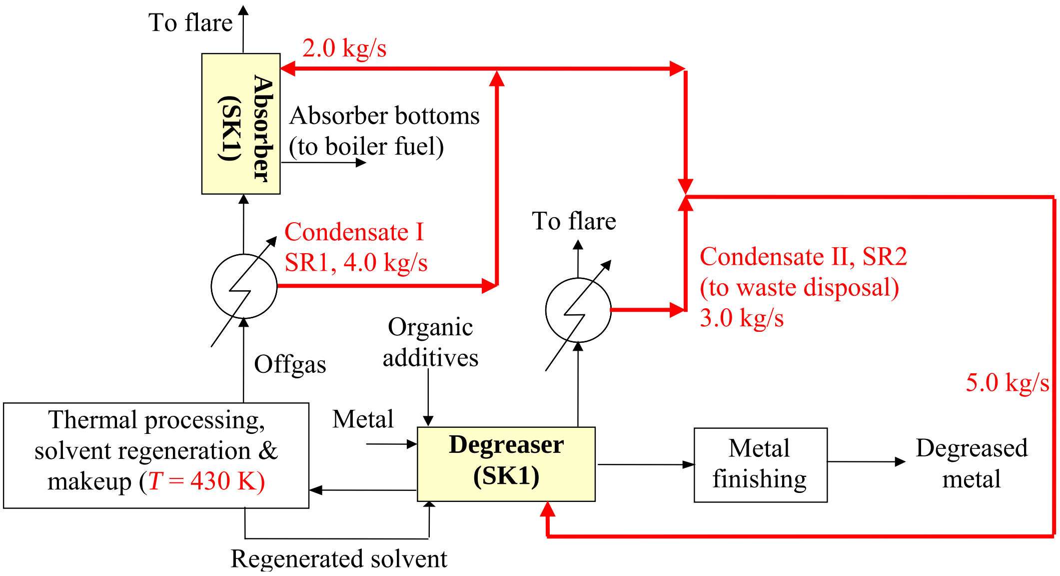


Figure 7.8 Network design for metal degreasing process after process modification

7.7 Papermaking process (Example 7.2)

Previous sections of the chapter have shown how PCA can be used to assess the various recycle/reuse and process modification strategies in a metal degreasing process. Note that the fresh solvent that is used in the degreasing process is fed at the lowest operator level compared to all other process sources (see Table 7.1). Unlike the cases in water and utility gas network synthesis, fresh process feed in property integration problems do not always available at the highest (or "superior") operator level except in some cases. Note also that this has an effect on how the limiting data is extracted for the case study. We will demonstrate the use of PCA to handle cases with fresh feed of lowest (or "inferior") operator value using the following example.

Figure 7.9 shows a papermaking process taken from Kazantzi and El-Halwagi (2005) and EL-Halwagi *et al.* (2004). Wood chips are digested and chemically treated in the Kraft digester before the produced pulp is sent to the bleaching section. The product from this section, i.e. bleached fibre is then sent to two paper machines (Paper Machine I and II), where they are converted into final paper products. Rejected products from Machine I are further treated in Hydro Pulper and Hydro Sieve before the waste and waste fibre streams (broke) are finally discharged. However, due to environmental concerns, it is proposed to recycle the broke back to the process.

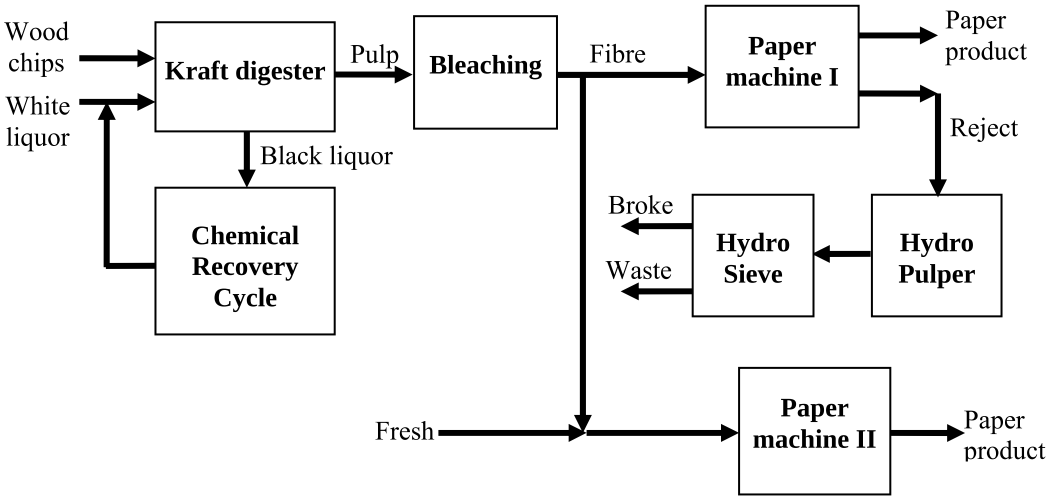


Figure 7.9 A papermaking process (Kazantzi and El-Halwagi, 2005)

The candidates that can be regarded as process sinks, where waste fibre is recycled, are the two paper machines. An external fresh fibre source is currently fed to paper machine II to supplement its fibre need. Thus, by recycling the broke, resource usage is maximised and fresh fibre consumption can be reduced. To evaluate the quality of the broke to be used as a feed stream to the sinks, we focus on reflectivity R_∞ , which is a dimensionless property for the produced paper. It is defined as the reflectance of an infinitely thick material compared to an absolute standard, i.e. magnesium oxide. The mixing rule for R_∞ has been given in Table 2.1.

Flowrate and reflectivity data for the fibre sinks and sources are given in the first four columns of Table 7.4. As shown, the fresh fibre feed possesses a reflectivity value of 0.95, which is at the highest level compared to all other limiting operators. In order to minimise the usage of the fresh feed, we shall define the lower bound of the reflectivity value to be the limiting operators of the process sinks. This, in turn, leads to lower limiting loads required by the process sinks (compared to that defined by the upper bound as the limiting operator). Limiting operators and loads for all fibre sinks and sources are listed in the final two columns of Table 7.4.

Table 7.4 Limiting data for Example 7.2 (papermaking process)

Process	**Flowrate (ton/h)**	**R_∞ (dimensionless)**		**Operator, Ψ (dimensionless)**	**Load, Δm (ton/h)**
		Lower bound	**Lower bound**		
(Sink)					
Paper Machine I	100	0.85	0.95	0.382	38.209
Paper Machine II	40	0.90	0.95	0.536	21.438
(Source)					
Process Fibre	90	0.88		0.469	42.226
Broke	60	0.75		0.182	10.927
Fresh fibre	To be determined	0.95		0.738	Nil

PCA is carried out to locate the minimum resource targets for the example. Note that, since the fresh fibre feed possesses a higher operator value (or is “inferior” to the other sources), the operators are arranged in descending order, in contrast to the metal degreasing process. Result of the PCA is shown in the PCT in Table 7.5. The minimum fresh fibre feed (F_F) and discharged flowrate (F_D) are easily identified from the PCT as 14.95 ton/h and 24.95 ton/h respectively (Table 7.5). These resource targets agree with those obtained by Kazantzi and El-Halwagi (2005). In addition, PCT also identifies the broke stream as the pinch-causing stream from which 35.05 ton/h is fed to the region above the pinch; whereas 25.95 ton/h goes to the region below the pinch, with the final network design shown in Figure 7.10.

Table 7.5 PCT for papermaking process (Example 7.2)

Level, *k*	ψ_k	**$\Sigma_j F_j$ (ton/h)**	**$\Sigma_i F_i$ (ton/h)**	**$\Sigma_i F_i - \Sigma_j F_j$ (ton/h)**	**$F_{C,k}$ (ton/h)**	**Δm_k (ton/h)**	**Cum. Δm_k (ton/h)**
					F_F = 14.95		
1	0.738						
					14.95	3.02	
2	0.536	-40		-40			3.02
					-25.05	-1.67	
3	0.469		90	90			1.35
					64.95	5.66	
4	0.382	-100		-100			7.01
					-35.05	-7.01	
5	0.182		60	60			**0**
					F_D = 24.95	4.54	**(PINCH)**
6	0.000						4.54

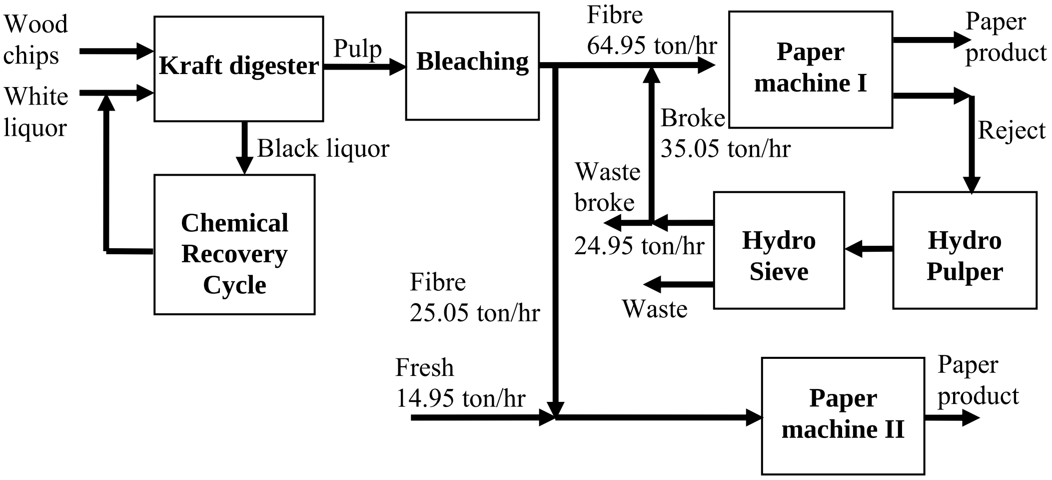


Figure 7.10 Final configuration of the papermaking process

7.8 Conclusion

This chapter presents the developments of a graphical technique called property surplus diagram and property cascade analysis (PCA) to establish the resource targets within a property integration framework. As an algebraic alternative to the surplus diagram, PCA quickly yields accurate resource targets, pinch locations, as well as material allocation targets for a property-based network, ahead of detailed network design. A procedure for synthesis of a maximum resource recovery (MRR) network has also been presented. To further reduce resource consumption in a property-based network, a systematic procedure to identify scope for process modifications has been outlined. The procedures developed in this chapter constitute a generalisation to the concentration-based graphical and cascade analysis techniques developed for water and utility gas networks in previous chapters.

CHAPTER 8

CONCLUSIONS AND FUTURE WORKS

8.1 Summary and significance

The work in this thesis offers some major contributions in the area of process synthesis, in particular, in the area of resource conservation networks (RCNs). This work presented a numerically efficient cascade analysis technique for setting minimum fresh feed and discharge flowrate targets for RCNs.

The newly developed cascade analysis technique is applied to continuous and batch water network, in which it is called the water cascade analysis (WCA) technique. WCA handles both mass transfer-based and non-mass transfer-based water-using operations and helps in the assessment of various options for process changes, including water regeneration, equipment modifications and optimisation towards zero discharge. The extension of WCA technique, i.e. time-dependent water cascade analysis (TDWCA) technique is used for water flowrates targeting in a batch water network.

In the application of gas cascade analysis (GCA) technique in various utility gas networks, different industrial processes involving the integration of nitrogen, oxygen and hydrogen gases are solved. Appropriate placement of gas purification units is also being assessed.

In the application of cascade analysis technique in property-based network, two new tools were developed. With the introduction of *property surplus diagram*, a basic framework for the determination of the minimum fresh feed and discharge targets is provided. The property cascade analysis (PCA) technique is next established to set targets via a tabular approach. Process modification is also being assessed using PSA.

Although many excellent targeting tools (e.g. Alves and Towler, 2002; Hallale, 2002; El-Halwagi *et al.*, 2003; Prakash and Shenoy, 2005) have been developed recently in the synthesis problem of RCNs, there are several cases when an algebraic approach such as the cascade analysis technique is desirable. These cases include:

i. Scaling problems: when the driving force (e.g. impurity concentration, property operator) and loads of process sources or sinks are of different magnitudes, the accuracy of the graphical approach becomes questionable since the graph will be skewed by the larger loads and operators.
ii. Problem dimensionality: when there are numerous sources and sinks, there is a need to handle the data algebraically in favour of graphically.
iii. Computational effectiveness: the algebraic procedures can be easily automated and coded to enhance computational effectiveness. This serves several purposes. For instance, in sensitivity analysis, the algebraic technique can be readily used to assess the solution sensitivity to variations in input data by running what-if scenarios. Graphical procedures are cumbersome in sensitivity analysis, since they may entail the re-plotting of the composite curves for each variation.
iv. Interaction with process simulators: the algebraic procedure is naturally implemented on a spreadsheet. Many computer-aided process simulation tools are interactive with spreadsheets. Hence, the resource utilisation information can be automatically extracted from the simulation and the targeted results from the spreadsheet are fed back to the simulator.

8.2 Future works

Since the work on RCN synthesis is relatively new, four main areas for future development can be identified:

i. Multiple component systems

In this thesis, only RCNs synthesis problem involving a single component has been covered. However, it is often necessary to consider cases involving multiple components since they are the more common. El-Halwagi and Manousiouthakis (1989) first presented their approach in handling the multiple component problems in the synthesis of mass exchange network (MEN) by first identifying the “pinched” component. MEN are designed based on the pinched component. It is assumed that the MEN designed for the pinched component is capable of delivering the required mass exchange task for all other components. The same approach can be extended into the synthesis problem of RCNs.

ii. Minimisation of water storage tanks for batch water network

A basic assumption underlying the synthesis of batch water network is that, water storage tanks are always available for any water reuse purpose. Note also that, to ensure the maximum water reuse among all water-using processes, mixing of water sources at different purities are to be avoided. Mixing of water sources of different purity levels degrade the potential of water reuse. Hence, number of water storage tanks utilised in a maximum water recovery (MWR) network will be essentially equal to the number of water sources (at different purity level) that were intended for reuse. The above-mentioned assumption indicates a potential pitfall for the work. Once the number of water source for reuse increases, the complexity of the network will increase. This is particular important when more water sources exist in the network. For a batch water network, it is important to keep the network configuration simple and flexible. Hence, new approached should be developed to improve the developed method in synthesising simple and flexible water network for a batch process system.

iii. Simultaneous analysis of batch, semi-batch and continuous processes

Previous work on heat (Kemp and Deakin, 1989a, b) and mass integration (Foo *et al.*, 2004, 2005a) pointed out that continuous process is in fact, a special case of batch process, with only one time interval. Their works indicated that it is possible to simultaneously integrate batch, semi-batch and continuous processes together. The strategy is to carefully arrange these processes so that they could be efficiently integrated. A continuous process will take place during all time intervals, whereas batch and semibatch processes will appear in some of the time intervals. RCN targeting and design could be carried out independently for each time interval.

iv. Further development of property-based network

Apart from considering multiple properties (similar to multiple components problems) in a property-based network, the future work in property-based network include that of the targeting and design for network where fresh resource lies neither at the highest (superior) or lowest (inferior) property operator level. The work developed in this thesis is limited to the application of property operator of fresh feed at the highest or lowest property operator level. In certain property-based network synthesis problems, the network calls for the use of fresh feed that is neither the highest or lowest property operator.

v. Incorporation of process and structural constraints

This work has mainly focused on targeting of minimum fresh feed and discharge flowrates. Other important aspects to be considered during network synthesis are process and structural-dependant issues. When reuse/recycle opportunities are identified, process sinks and sources must be physically linked to enable integration to take place. The inclusion of candidates that are physically located far apart may lead to expensive piping and instrumentation costs. Hence, the trade-off between saving vs. investment needs to be considered to identify a economically viable project.

Besides, there may be other process constraints such as certain operations that must be linked (termed as *compulsory match*) to enable operations to take place; and other operations that must not be linked (termed as *forbidden match*) to avoid contaminant built up, etc. All these aspects needs further investigation in future works.

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APPENDIX A – WATER CASCADE TABLES FOR OTHER CASE STUDIES

Note: Case studies that are not presented in Chapter 4 (Result and Discussion – Water Cascade Analysis) are listed here.

Example A.1 (Kuo and Smith, 1998)

Table A.1 Limiting water data for Example A.1 (Kuo and Smith, 1998)

Water sink, SK$_j$	**Flowrate, F_j (ton/h)**	**Concentration, C_j (ppm)**	**Water source, SR$_i$**	**Flowrate, F_i (ton/h)**	**Concentration, C_i (ppm)**
1	40	0	1	40	200
2	50	100	2	50	200
3	30	100	3	30	400
4	60	300	4	60	400
5	40	400	5	40	600

Table A.2 WCT for Example A.1

k	**C_k (ppm)**	**$\Sigma_j F_j$ (ton/h)**	**$\Sigma_i F_i$ (ton/h)**	**$\Sigma_i F_i - \Sigma_j F_j$ (ton/h)**	**$F_{C,k}$ (ton/h)**	**Δm_k (kg/h)**	**Cum. Δm_k (kg/h)**
					F_F = 80		
1	0	40		-40			
					40	4	
2	100	80		-80			4
					-40	-4	
3	200		90	90			**0** **(PINCH)**
					50	5	
4	300	60		-60			5
					-10	-1	
5	400	40	90	50			4
					40	8	
6	600		40	40			12
					F_D = 80	79952	
7	1000000						79964

Example A.2 (Castro *et al.*, 1999)

Table A.3 Limiting water data for Example A.2 (Castro *et al.*, 1999)

Water sink, SK$_j$	**Flowrate, F_j (ton/h)**	**Concentration, C_j (ppm)**	**Water source, SR$_i$**	**Flowrate, F_i (ton/h)**	**Concentration, C_i (ppm)**
1	25	0	1	25	250
2	60	50	2	60	300
3	30	150	3	30	400
4	70	300	4	70	500

Table A.4 WCT for Example A.2

k	**C_k (ppm)**	**$\Sigma_j F_j$ (ton/h)**	**$\Sigma_i F_i$ (ton/h)**	**$\Sigma_i F_i - \Sigma_j F_j$ (ton/h)**	**$F_{C,k}$ (ton/h)**	**Δm_k (kg/h)**	**Cum. Δm_k (kg/h)**
					F_F = 89.375		
1	0	25		-25			
					64.375	3.219	
2	50	60		-60			3.219
					4.375	0.438	
3	150	30		-30			3.656
					-25.625	-2.563	
4	250		25	25			1.094
					-0.625	-0.031	
5	300	70	60	-10			1.063
					-10.625	-1.063	
6	400		30	30			**0.000**
					19.375	1.938	**(PINCH)**
7	500		70	70			1.938
					F_D = 89.375	89330.313	
8	1000000						89332.250

Example A.3 (Yang *et al.*, 1999)

Table 5 Limiting water data for Example A.3 (Yang *et al.*, 1999)

Water sink, SK$_j$	**Flowrate, F_j (ton/h)**	**Concentration, C_j (ppm)**	**Water source, SR$_i$**	**Flowrate, F_i (ton/h)**	**Concentration, C_i (ppm)**
1	35	0	1	35	200
2	56	100	2	56	500
3	139	200	3	139	650
4	10	0	4	10	200

Table 6 WCT for Example A.3

k	C_k (ppm)	$\Sigma_j F_j$ (ton/h)	$\Sigma_i F_i$ (ton/h)	$\Sigma_i F_i - \Sigma_j F_j$ (ton/h)	$F_{C,k}$ (ton/h)	Δm_k (kg/h)	Cum. Δm_k (kg/h)
					F_F = 146.2		
1	0	-45		-45			
					101.2	10.12	
2	100	-56		-56			10.12
					45.2	4.52	
3	200	-139	45	-94			14.64
					-48.8	-14.64	
4	500		56	56			**0.00**
					7.2	1.08	**(PINCH)**
5	650		139	139			1.08
					F_D = 146.2	146104.97	
6	1000000						146106.05

Example A.4 – textile manufacturing (Ujang *et al.*, 2002)

Table A.7 Limiting water data for Example A.4 (Ujang *et al.*, 2002)

Water sinks, SK_j		**Flowrate**	**Concentration**
j	**Stream**	**F_j (ton/h)**	**C_j (ppm)**
1	Singeing	2.67	0
2	Mercerizing	22.77	75
3	Bleaching	18.17	47
Water sources, SR_i		**Flowrate**	**Concentration**
i	**Stream**	**F_i (ton/h)**	**C_i (ppm)**
1	Singeing	2.67	47
2	Mercerizing	22.77	476
3	Bleaching	18.17	3218

Table A.8 WCT for Example A.4

k	C_k (ppm)	$\Sigma_j F_j$ (ton/h)	$\Sigma_i F_i$ (ton/h)	$\Sigma_i F_i - \Sigma_j F_j$ (ton/h)	$F_{C,k}$ (ton/h)	Δm_k (kg/h)	Cum. Δm_k (kg/h)
					F_F = 35.822		
1	0	-2.67		-2.67			
					33.152	1.558	
2	47	-18.17	2.67	-15.5			1.558
					17.652	0.494	
3	75	-22.77		-22.77			2.052
					-5.118	-2.052	
4	476		22.77	22.77			**0.000**
					17.652	48.401	**(PINCH)**
5	3218		18.17	18.17			48.401
					F_D = 35.822	35706.553	
6	1000000						35754.954

Example A.5 (Savelski and Bagajewicz, 2001; Bagajewicz and Savelski, 2001)

Table A.9 Limiting water data for Example A.5 (Savelski and Bagajewicz, 2001; Bagajewicz and Savelski, 2001)

Water sink, SK$_j$	**Flowrate, F_j (ton/h)**	**Concentration, C_j (ppm)**	**Water source, SR$_i$**	**Flowrate, F_i (ton/h)**	**Concentration, C_i (ppm)**
1	36.364	25	1	36.364	80
2	44.308	25	2	44.308	90
3	22.857	25	3	22.857	200
4	60.000	50	4	60.000	100
5	40.000	50	5	40.000	800
6	12.500	400	6	12.500	800
7	5.000	200	7	5.000	600
8	10.000	0	8	10.000	100
9	80.000	50	9	80.000	300
10	43.333	150	10	43.333	300

Table A.10 WCT for Example A.5

k	**C_k (ppm)**	**$\Sigma_j F_j$ (ton/h)**	**$\Sigma_i F_i$ (ton/h)**	**$\Sigma_i F_i - \Sigma_j F_j$ (ton/h)**	**$F_{C,k}$ (ton/h)**	**Δm_k (kg/h)**	**Cum. Δm_k (kg/h)**
					F_F = 166.267		
1	0	10.00		-10.00			
					156.267	3.907	
2	25	103.53		-103.53			3.907
					52.738	1.318	
3	50	180.00		-180.00			5.225
					-127.262	-3.818	
4	80		36.36	36.36			1.407
					-90.898	-0.909	
5	90		44.31	44.31			0.498
					-46.590	-0.466	
6	100		70.00	70.00			0.032
					23.410	1.170	
7	150	43.33		-43.33			1.203
					-19.924	-0.996	
8	200	5.00	22.86	17.86			0.207
					-2.067	-0.207	
9	300		123.33	123.33			**0.000** **(PINCH)**
					121.267	12.127	
10	400	12.50		-12.50			12.127
					108.767	21.753	
11	600		5.00	5.00			33.880
					113.767	22.753	
12	800		52.50	52.50			56.633
					F_D = 166.267	166133.65	
13	1000000						166190.3

Example A.6 (Lovelady *et al.*, 2006)

Table A.11 Limiting water data for Example A.6 (Lovelady *et al.*, 2006)

Water sink, SK$_j$	**Flowrate, F_j (ton/d)**	**Concentration, C_j (ppm)**	**Water source, SR$_i$**	**Flowrate, F_i (ton/d)**	**Concentration, C_i (ppm)**
1	1450	4.5	1	8901	0
2	13995	6.8	2	10995	35.8

Table A.12 WCT for Example A.6

k	**C_k (ppm)**	**$\Sigma_j F_j$ (ton/d)**	**$\Sigma_i F_i$ (ton/d)**	**$\Sigma_i F_i - \Sigma_j F_j$ (ton/d)**	**$F_{C,k}$ (ton/d)**	**Δm_k (kg/d)**	**Cum. Δm_k (kg/d)**
					0.00		
1	0		8901	8901			
					8901.00	32.93	
2	3.7			**F_F = 4130.35**			32.93
					13031.35	10.43	
3	4.5	1450		-1450			43.36
					11581.35	26.64	
4	6.8	13995		-13995			70.00
					-2413.65	-70.00	
5	35.8		10995	10995			**0.00**
					F_D = 8581.35	8581041	**(PINCH)**
6	1000000						8581041

Example A.7 (Savelski and Bagajewicz, 2001)

Table A.13 Limiting water data for Example A.7 (Savelski and Bagajewicz, 2001)

Water sink, SK$_j$	**Flowrate, F_j (ton/h)**	**Concentration, C_j (ppm)**	**Water source, SR$_i$**	**Flowrate, F_i (ton/h)**	**Concentration, C_i (ppm)**
1	12.500	0	1	12.500	80
2	20.000	0	2	20.000	100
3	16.667	0	3	16.667	120
4	36.364	25	4	36.364	80
5	44.308	25	5	44.308	90
6	30.000	40	6	30.000	90
7	60.000	50	7	60.000	100
8	88.889	75	8	88.889	120
9	22.857	25	9	22.857	200
10	133.333	75	10	133.333	150
11	100.000	120	11	100.000	200
12	18.000	200	12	18.000	300
13	88.889	75	13	88.889	300
14	43.333	150	14	43.333	300
15	5.000	200	15	5.000	600
16	40.000	50	16	40.000	800
17	12.500	400	17	12.500	800
18	70.000	400	18	70.000	500
19	10.200	600	19	10.200	850
20	4.000	800	20	4.000	950

Table A.14 WCT for Example A.7

k	C_k (ppm)	$\Sigma_j F_j$ (ton/h)	$\Sigma_i F_i$ (ton/h)	$\Sigma_i F_i - \Sigma_j F_j$ (ton/h)	$F_{C,k}$ (ton/h)	Δm_k (kg/h)	Cum. Δm_k (kg/h)
					F_F = 299.359		
1	0	49.167		-49.167			
					250.19206	6.255	
2	25	103.528		-103.528			6.255
					146.66359	2.200	
3	40	30.000		-30.000			8.455
					116.66359	1.167	
4	50	100.000		-100.000			9.621
					16.663592	0.167	
5	60			0.000			9.788
					16.663592	0.250	
6	75	311.111		-311.111			10.038
					-294.4475	-1.472	
7	80		48.864	48.864			8.566
					-245.5839	-2.456	
8	90		74.308	74.308			6.110
					-171.2762	-1.713	
9	100		80.000	80.000			4.397
					-91.27619	-1.826	
10	120	100.000	105.556	5.556			2.572
					-85.72063	-2.572	
11	150	43.333	133.333	90.000			**0.000**
					4.2793651	0.214	**(PINCH)**
12	200	23.000	122.857	99.857			0.214
					104.13651	10.414	
13	300		150.222	150.222			10.628
					254.35873	25.436	
14	400	82.500		-82.500			36.063
					171.85873	17.186	
15	500		70.000	70.000			53.249
					241.85873	24.186	
16	600	10.200	5.000	-5.200			77.435
					236.65873	47.332	
17	800	4.000	52.500	48.500			124.767
					285.15873	14.258	
18	850		10.200	10.200			139.025
					295.35873	29.536	
19	950		4.000	4.000			168.561
					F_D = 299.359	299074.34	
20	1000000						299242.9

Example A.8 (Jacob *et al.*, 2002; El-Halwagi *et al.*, 2003)

Table A.15 Limiting water data for Example A.8 (Jacob *et al.*, 2002; El-Halwagi *et al.*, 2003)

Water sink, SK_j	Flowrate, F_j (L/min)	Concentration, C_j (%)	Water source, SR_i	Flowrate, F_i (L/min)	Concentration, C_i (%)
1	2195	0	1	25000	0.07
2	1970	0.018	2	39000	0.13
3	355	0.02	3	5980	0.5
4	132005	1	4	2840	0.49
			5	6840	0.08
			6	3720	0.1
			7	73000	0.39
			8	8585	0.34
			9	2570	0
			10	1940	0.13

Table A.16 WCT for Example A.8

k	C_k (%)	$\Sigma_j F_j$ (L/min)	$\Sigma_i F_i$ (L/min)	$\Sigma_i F_i - \Sigma_j F_j$ (L/min)	$F_{C,k}$ (L/min)	Δm_k (L/min)	Cum. Δm_k (L/min)
					F_F = 1342		
1	0	2195	2570	375			
					1717	30.91	
2	0.02	1970		-1970			30.91
					-253	-0.51	
3	0.02	355		-355			30.40
					-608	-30.40	
4	0.07		25000	25000			**0.00**
					24392	243.92	**(PINCH)**
5	0.08		6840	6840			243.92
					31232	624.64	
6	0.10		3720	3720			868.56
					34952	1048.56	
7	0.13		40940	40940			1917.12
					75892	15937.32	
8	0.34		8585	8585			17854.44
					84477	4223.85	
9	0.39		73000	73000			22078.29
					157477	15747.70	
10	0.49		2840	2840			37825.99
					160317	1603.17	
11	0.50		5980	5980			39429.16
					166297	83148.50	
12	1.00	132005		-132005			122577.66
					F_D = 34292	3394908.00	
13	100						3517485.66

Example A.9 – paper milling process (Tan and Manan, 2003)

Table A.17 Limiting water data for Example A.9 (Tan and Manan, 2003)

Water sinks, SK_j		**Flowrate**	**Concentration**
j	**Stream**	F_j **(ton/h)**	C_j **(ppm)**
1	Pressing showers	155.4	20
2	Forming showers	831.12	80
3	Others	201.84	100
4	DIP	1149.84	200
5	DAF	499.8	250
6	Saveall Disc Filter	1264.5	250
7	Approach Flow	34.68	20
8	Chemical Preparation	68.7	200
Water sources, SR_i		**Flowrate**	**Concentration**
i	**Stream**	F_i **(ton/h)**	C_i **(ppm)**
1	Pressing showers	155.4	100
2	Forming showers	1305.78	230
3	Others	201.84	170
4	DIP	469.8	250
5	DAF	490.8	170
6a	Saveall Disc Filter	721.14	100
6b	Saveall Disc Filter	68.7	200
6c	Saveall Disc Filter	474.66	230

Table A.18 WCT for Example A.9

k	C_k **(ppm)**	$\Sigma_j F_j$ **(ton/h)**	$\Sigma_i F_i$ **(ton/h)**	$\Sigma_i F_i - \Sigma_j F_j$ **(ton/h)**	$F_{C,k}$ **(ton/h)**	Δm_k **(kg/h)**	**Cum.** Δm_k **(kg/h)**
					F_F **= 329.90**		
1	0						
					329.90	6598.09	
2	20	190.08	0	-190.08			6598.09
					139.82	8389.48	
3	80	831.12	0	-831.12			14987.58
					-691.30	-13825.91	
4	100	201.84	876.54	674.7			1161.67
					-16.60	-1161.67	
5	170	0	692.64	692.64			**0.00**
					676.04	20281.34	**(PINCH)**
6	200	1218.54	68.7	-1149.84			20281.34
					-473.80	-14213.86	
7	230	0	1780.44	1780.44			6067.48
					1306.64	26132.89	
8	250	1764.3	469.8	-1294.5			32200.38
					F_D **= 12.14**	12141669	
9	1000000						12173870

Example A.10 – paper milling process (Manan *et al.*, 2006)

Table A.19 Limiting water data for Example A.10 (Manan *et al.*, 2006)

Water sinks, SK_j		**Flowrate**	**Concentration**
j	**Stream**	**F_j (ton/h)**	**C_j (ppm)**
1	Pressing 1	126	20
2	Forming 1	54	20
3	Deculator 1	18	20
4	Chemical Preparation	36	20
5	Clarifies Water Tower 1	201.6	20
6	Pressing 2	169.2	100
7	Clarifies Water Tower 2	1130.4	150
8	Pressing 3	676.8	160
9	Forming 2	154.8	160
10	Deculator 2	104.4	160
11	DIP	396	160
12	Deculator 3	68.4	250
Water sources, SR_i		**Flowrate**	**Concentration**
i	**Stream**	**F_i (ton/h)**	**C_i (ppm)**
1	Saveall Disc Filter 1	169.2	100
2	DAF 92	435.6	150
3	Saveall Disc Filter 2	1130.4	150
4	Classified water tower	1332	160
5	Saveall Disc Filter 3	68.4	250

Table A.20 WCT for Example A.10

k	**C_k (ppm)**	**$\Sigma_j F_j$ (ton/h)**	**$\Sigma_i F_i$ (ton/h)**	**$\Sigma_i F_i - \Sigma_j F_j$ (ton/h)**	**$F_{C,k}$ (ton/h)**	**Δm_k (kg/h)**	**Cum. Δm_k (kg/h)**
					F_F = 377.52		
1	0						
					377.52	7550.40	
2	20	435.6		-435.6			7550.40
					-58.08	-4646.40	
3	100	169.2	169.2	0			2904.00
					-58.08	-2904.00	
4	150	1130.4	1566	435.6			**0.00** **(PINCH)**
					377.52	3775.20	
5	160	1332	1332	0			3775.20
					377.52	33976.80	
6	250	68.4	68.4	0			37752.00
					F_D = 377.52	377425620	
7	1000000						377463372

Example A.11 – Tricresyl phosphate process (El-Halwagi, 1997)

Table A.21 Limiting water data for Example A.11 (El-Halwagi, 1997)

Water sinks, SK$_j$		**Flowrate**	**Concentration**
j	**Stream**	**F_j (kg/s)**	**C_j (ppm)**
1	Washing I	2.45	5
2	Washing II	2.45	0
3	Scrubber I	0.70	30
4	Scrubber II	0.50	30
5	Flare seal pot	0.20	100
Water sources, SR$_i$		**Flowrate**	**Concentration**
i	**Stream**	**F_i (kg/s)**	**C_i (ppm)**
1	Washing I	2.45	76.36
2	Washing II	2.45	0.07
3	Scrubber I	0.70	410.57
4	Scrubber II	0.50	144
5	Flare seal pot	0.20	281.5

Table A.22 WCT for Example A.11

k	**C_k (ppm)**	**$\Sigma_j F_j$ (kg/s)**	**$\Sigma_i F_i$ (kg/s)**	**$\Sigma_i F_i - \Sigma_j F_j$ (kg/s)**	**$F_{C,k}$ (kg/s)**	**Δm_k (mg/s)**	**Cum. Δm_k (mg/s)**
					F_F = 3.02		
1	0.00	2.45		-2.45			
					0.57	0.04	
2	0.07		2.45	2.45			0.04
					3.02	14.89	
3	5.00	2.45		-2.45			14.93
					0.57	14.26	
4	30.00	1.2		-1.2			29.19
					-0.63	-29.19	
5	76.36		2.45	2.45			**0.00**
					1.82	43.03	**(PINCH)**
6	100.00	0.2		-0.2			43.03
					1.62	71.30	
7	144.00		0.5	0.5			114.33
					2.12	291.55	
8	281.50		0.2	0.2			405.88
					2.32	299.49	
9	410.57		0.7	0.7			705.37
					F_D = 3.02	3019131	
10	1000000						3019836

Example A.12 – Ethyl chloride process (El-Halwagi, 1997)

Table A.23 Limiting water data for Example A.12 (El-Halwagi, 1997)

Water sinks, SK$_j$		**Flowrate**	**Concentration**
j	**Stream**	**F_j (kg/s)**	**C_j (ppm)**
1	Reactor	0.09	65
2	Scrubber I	0.075	8
3	Scrubber II	0.075	0
Water sources, SR$_i$		**Flowrate**	**Concentration**
i	**Stream**	**F_i (kg/s)**	**C_i (ppm)**
1	Reactor	0.09	7.2
2	Scrubber I	0.08	90
3	Scrubber II	0.08	9

Table A.24 WCT for Example A.12

k	**C_k (ppm)**	**$\Sigma_j F_j$ (kg/s)**	**$\Sigma_i F_i$ (kg/s)**	**$\Sigma_i F_i - \Sigma_j F_j$ (kg/s)**	**$F_{C,k}$ (kg/s)**	**Δm_k (mg/s)**	**Cum. Δm_k (mg/s)**
					F_F = 0.075		
1	0	0.075		-0.075			
					0	0.00	
2	7.2		0.09	0.09			**0.00 (PINCH)**
					0.09	0.07	
3	8	0.075		-0.075			0.07
					0.015	0.02	
4	9		0.08	0.075			0.09
					0.09	5.04	
5	65	0.09		-0.09			5.13
					0	0.00	
6	90		0.08	0.075			5.13
					F_D = 0.075	74993.25	
7	1000000						74998.38

Example A.13 (Koppol & Bagajewicz, 2003)

Table A.25 Limiting water data for Example A.13 (Koppol & Bagajewicz, 2003)

Water sink, SK_j	Flowrate, F_j (ton/h)	Concentration, C_j (ppm)	Water source, SR_i	Flowrate, F_i (ton/h)	Concentration, C_i (ppm)
1	36.36	25	1	36.36	80
2	36.00	10	2	36.00	90
3	22.86	25	3	22.86	200
4	60.00	50	4	60.00	100
5	12.50	400	5	12.50	800
6	43.33	150	6	43.33	300

Table A.26 WCT for Example A.13

k	C_k (ppm)	$\Sigma_j F_j$ (ton/h)	$\Sigma_i F_i$ (ton/h)	$\Sigma_i F_i - \Sigma_j F_j$ (ton/h)	$F_{C,k}$ (kg/h)	Δm_k (kg/h)	Cum. Δm_k (kg/h)
					F_F = 97.40		
1	0						
					97.40	973.97	
2	10	36.00		-36.00			973.97
					61.40	920.95	
3	25	59.22		-59.22			1894.92
					2.18	54.40	
4	50	60.00		-60.00			1949.32
					-57.82	-1734.72	
5	80		36.36	36.36			214.60
					-21.46	-214.60	
6	90		36.00	36.00			**0.00 (PINCH)**
					14.54	145.40	
7	100		60.00	60.00			145.40
					74.54	3726.98	
8	150	11.00		-11.00			3872.38
					31.21	1560.32	
9	200		22.86	22.86			5432.70
					54.06	5406.35	
10	300		43.33	43.33			10839.05
					97.40	9739.68	
11	400	12.50		-12.50			20578.73
					84.90	33958.73	
12	800		12.50	12.50			54537.46
					F_D = 97.40	97318907.94	
13	1000000						97373445.40

Example A.14 - Kraft pulping process (El-Halwagi, 1997; Foo *et al.*, 2006)

Table A.27 Limiting water data for Example A.14 (El-Halwagi, 1997; Foo *et al.*, 2006)

Water sinks, SK_j		**Flowrate**	**Concentration**
j	**Stream**	F_j **(kg/s)**	C_j **(ppm)**
1	Pulp washing	467	20
2	Chemical recovery	165	20
3	Condenser	8.2	10
Water sources, SR_i		**Flowrate**	**Concentration**
i	**Stream**	F_i **(kg/s)**	C_i **(ppm)**
1	W3	12.98	419
2	W5	9.7	16248
3	W7	10.78	9900
4	W8	116.5	20
5	W9	48	233
6	W10	52	311
7	W11	52.2	20
8	W13	300	30
9	W14	140	15

Table A.28 WCT for Example A.14

k	C_k (ppm)	$\Sigma_j F_j$ (ton/h)	$\Sigma_i F_i$ (ton/h)	$\Sigma_i F_i - \Sigma_j F_j$ (ton/h)	$F_{C,k}$ (kg/h)	Δm_k (kg/h)	Cum. Δm_k (kg/h)
					F_F = 89.90		
1	0						
					89.90	0.90	
2	10	8.2		-8.2			0.90
					81.70	0.41	
3	15		140	140			1.31
					221.70	1.11	
4	20	632	168.7	-463.3			2.42
					-241.60	-2.42	
5	30		300	300			**0.00** **(PINCH)**
					58.40	11.86	
6	233		48	48			11.86
					106.40	8.30	
7	311		52	52			20.15
					158.40	17.11	
8	419		12.98	12.98			37.26
					171.38	1624.85	
9	9900		10.78	10.78			1662.12
					182.16	1156.35	
10	16248		9.7	9.7			2818.47
					F_D = 191.86	188742.66	
11	1000000						

Example A.15 (Liu *et al.*, 2004)

Table A.29 Limiting water data for Example A.15 (Liu *et al.*, 2004)

Water sink, SK$_j$	**Flowrate, F_j (ton/h)**	**Concentration, C_j (ppm)**	**Water source, SR$_i$**	**Flowrate, F_i (ton/h)**	**Concentration, C_i (ppm)**
1	14.59	6	1	25.83	322.7
2	58.33	6.4	2	15	15.6
3	58.33	2.1	3	15	10.8
4	2.5	20	4	2.5	207
5	1.75	0	5	1.75	3

Table A.30 WCT for Example A.15

k	**C_k (ppm)**	**$\Sigma_j F_j$ (ton/h)**	**$\Sigma_i F_i$ (ton/h)**	**$\Sigma_i F_i - \Sigma_j F_j$ (ton/h)**	**$F_{C,k}$ (kg/h)**	**Δm_k (kg/h)**	**Cum. Δm_k (kg/h)**
					F_F = 102.63		
1	0	1.75		-1.75			
					100.88	211.85	
2	2.1	58.33		-58.33			211.85
					42.55	38.29	
3	3		1.75	1.75			250.14
					44.30	132.90	
4	6	14.59		-14.59			383.04
					29.71	11.88	
5	6.4	58.33		-58.33			394.92
					-28.62	-125.93	
6	10.8		15	15			268.99
					-13.62	-65.38	
7	15.6		15	15			203.60
					1.38	6.07	
8	20	2.5		-2.5			209.67
					-1.12	-209.67	
9	207		2.5	2.5			**0.00**
					1.38	159.52	**(PINCH)**
10	322.7		25.83	25.83			159.52
					F_D = 27.21	27199988	
11	1000000						27200147

Example A.16 – Palm oil milling (Chungsiriporn *et al.*, 2006)

Table A.31 Limiting water data for Example A.16 (Chungsiriporn *et al.*, 2006)

Water sinks, SK_j		**Flowrate**	**Concentration**
j	**Stream**	F_j **(ton/h)**	C_j **(%)**
1	Mixing water	14	0.03
2	Blending water	2.5	0.12
3	Phase balancing	7.5	0.093
Water sources, SR_i		**Flowrate**	**Concentration**
i	**Stream**	F_i **(ton/h)**	C_i **(%)**
1	Separator outlet	24	0.093
2	Sterilizer condensate	6	0.01
3	Cooling water	4	0

Table A.32 WCT for Example A.16

k	C_k **(%)**	$\Sigma_j F_j$ **(ton/h)**	$\Sigma_i F_i$ **(ton/h)**	$\Sigma_i F_i - \Sigma_j F_j$ **(ton/h)**	$F_{C,k}$ **(ton/h)**	Δm_k **(kg/s)**	**Cum.** Δm_k **(kg/s)**
					F_F **= 0.13**		
1	0		4	4			
					4.13	0.04	
2	0.01		6	6			0.04
					10.13	0.20	
3	0.03	14		-14			0.24
					-3.87	-0.24	
4	0.093	7.5	24	16.5			**0.00**
					12.63	0.34	**(PINCH)**
5	0.12	2.5		-2.5			0.34
					F_D **= 10.13**	8.91	
6	1						9.25

Example A.17 (Ku-Pineda and Tan, 2006)

Table A.33 Limiting water data for Example A.17 (Ku-Pineda and Tan, 2006)

Water sink, SK$_j$	**Flowrate, F_j (m^3/d)**	**Concentration, C_j (ppm)**	**Water source, SR$_i$**	**Flowrate, F_i (m^3/d)**	**Concentration, C_i (ppm)**
1	45.55	10	1	45.55	115
2	182.35	0	2	182.35	44
3	138.7	10	3	138.7	49
4	92.55	10	4	92.55	83
5	105	87	5	105	17

Table A.34 WCT for Example A.17

k	C_k (ppm)	$\Sigma_j F_j$ (m^3/d)	$\Sigma_i F_i$ (m^3/d)	$\Sigma_i F_i - \Sigma_j F_j$ (m^3/d)	$F_{C,k}$ (m^3/d)	Δm_k (g/d)	**Cum.** Δm_k (g/d)
					F_F **= 331.81**		
1	0	182.35		-182.35			
					149.46	1494.59	
2	10	276.8		-276.8			1494.59
					-127.34	-891.39	
3	17		105	105			603.20
					-22.34	-603.20	
4	44		182.35	182.35			**0.00**
					160.01	800.05	**(PINCH)**
5	49		138.7	138.7			800.05
					298.71	10156.11	
6	83		92.55	92.55			10956.15
					391.26	1565.04	
7	87	105		-105			12521.19
					286.26	8015.25	
8	115		45.55	45.55			20536.45
					F_D **= 331.81**	331770933	
9	1000000						331791470

APPENDIX B – REFEREED JOURNAL/MAGAZINE PUBLICATIONS

Manan, Z. A., Tan, Y. L. and Foo, D. C. Y. (2004). Targeting the Minimum Water Flowrate Using Water Cascade Analysis Technique. *AIChE Journal*. 50(12): 3169-3183.

Foo, D. C. Y., Manan, Z. A. and Tan, Y. L. (2005). Synthesis of Maximum Water Recovery Network for Batch Process Systems. *Journal of Cleaner Production*. 13(15): 1381-1394.

Foo, D. C. Y., Kazantzi, V., El-Halwagi, M. M. and Manan, Z. A. (2006). Cascade Analysis for Targeting Property-based Material Reuse Networks. *Chemical Engineering Science.* 61(8): 2626-2642.

Foo, D. C. Y., Manan, Z. A. and El-Halwagi, M. M. (2006). Correct Identification of Limiting Water Data for Water Network Synthesis. *Clean Technology and Environmental Policy*. 8(2): 96-104.

Foo, D. C. Y. (2006). Use Process Integration to Set Reuse and Recycling Targets, *Bulletin of Institution of Engineers, Malaysia*, 2006(4): 8-14.

Manan, Z. A., Tan, Y. L., Foo, D. C. Y. and Tea, S. Y. (2006). Application of Water Cascade Analysis Technique for Water Minimisation in a Paper Mill Plant. *International Journal of Environment and Pollution* (in press).

Manan, Z. A., Foo, D. C. Y. and Tan, Y. L. (2006). Use Cascade Analysis Technique to Set Baseline Targets and Optimise Water Network. *Chemical Engineering Progress*, Volume 101 (in press).

Foo, D. C. Y. and Manan, Z. A. (2006). Setting the Minimum Utility Gas Flowrate Targets Using Cascade Analysis Technique. *Industrial & Engineering Chemistry Research* (in review).