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Improved Composite Table Algorithm for Targeting Regeneration-Recycle Water Network

Reza Parand*[,a,b], Hong M. Yao[a], Dominic C.Y. Foo[c], Moses O. Tadé[a]

[a]Centre for Process Systems Computations, Department of Chemical Engineering, Curtin University, GPO Box U1987 Perth, WA 6845, Australia
[b]Australian Joint Research Centre for Building Information Modeling, School of Built Environment, Curtin University GPO Box U1987, Perth, WA 6845, Australia
[c] Department of Chemical and Environmental Engineering, University of Nottingham Malaysia, Broga Road, 43500 Semenyih, Selangor, Malaysia
reza.parand@curtin.edu.au

This work aims to improve the Composite Table Algorithm as a targeting tool for regeneration-recycle water network. It is demonstrated that some problems have the potential to achieve zero liquid discharge. A literature example on a petrochemical plant is used to show the applicability of the proposed method. MATLAB is utilised as a programming tool to facilitate the implementation of the developed method.

1. Introduction

Rapid depletion of resources has necessitated resource management policies to sustain future world population growth. Process Integration has been accepted as one of the powerful tools for water conservation (Sueviriyapan et al., 2014). Water minimisation in industrial processes can be addressed through process changes, water reuse/recycle, and water regeneration-reuse/recycle. Many Water Pinch Analysis methodologies have been developed for direct reuse/recycle network, varying from graphical tools such as limiting water profile (Wang and Smith, 1994), Material Recovery Pinch Diagram (El-Halwagi et al., 2003), water surplus diagram (Hallale, 2002), numerical techniques such as water cascade analysis (Manan et al., 2004) and hybrid method such as Composite Table Algorithm – CTA (Agrawal and Shenoy, 2006). Among these targeting techniques, the CTA (Agrawal and Shenoy, 2006) is a powerful tool due to its combined graphical and numerical characteristic. The CTA first generates data in a tabular form, and Limiting Composite Curve (LCC) is then constructed for graphical display. A review for these methods was done by Foo (2009).

The water network model is mainly classified into two categories, i.e. fixed load (FL) and fixed flow rate (FF) problems. In FL model, inlet and outlet water flow rates to the particular process are redeemed as the same. However, in the FF model, flow rate entering the process does not essentially equal to the outlet flow rate as water loss/gain may occur. For single contaminant problems, both FL and FF problems are interchangeable, and hence can be handled with the same targeting tools (Foo, 2009).

The first guideline for regeneration placement in the FF problems was proposed by Hallale (2002). Later El-Halwagi (2006) developed graphical Material Recovery Pinch Diagram targeting tool to locate the regeneration unit within the water regeneration network. Foo et al. (2006) proposed algebraic water cascade analysis for targeting regeneration-recycle network. Targeting for water regeneration network were also carried out using the CTA by Agrawal and Shenoy (2006). However, in dealing with highly integrated processes, i.e. where the turning point of LCC is not completely recognizable, this procedure is not completely reliable. To address this shortage, CTA is improved in this work using only algebriac procedure for both data generation and target identification steps. Note that the improved CTA for total regeneration water network has been developed recently (Parand et al., 2014). Here we focus on regeneration-recyle water network. A literature example based on petrochemical plant (Mann and Liu, 1999) is used to demonstrate the applicability of the proposed method.

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2. An improved CTA

The CTA is improved by adopting the concept of Feng et al. (2007) for targeting regeneration-recycle water network. The first five steps are identical to CTA procedure (Agrawal and Shenoy, 2006).
Step 1-Arrange limiting concentration including the largest arbitrary value in increasing order. Note that the post-regeneration concentration (C_0) should be included.
Step 2-Identify the interval net flowrate: For each concentration interval, the sum of flow rates of process sources is subtracted from the sum of flow rates of process sinks.
Step 3-Determine the interval impurity load: These values are calculated by multiplying the interval net flow rate with the difference of contaminant concentration levels.
Step 4-Calculate the cumulative load ($Cum\Delta m_k$): By assuming the zero impurity load as the first entry, the interval impurity load is cascaded down to generate the cumulative load.
Step 5-Deduce the interval freshwater flow rate for reuse/recycle network via Eq(1).

$$F_{fw,k} = \frac{Cum\Delta m_k}{C_k - C_{fw}}, \ \forall k \quad (1)$$

Now, the associated value to the C_0 is the minimum freshwater requirement (F_{fw}). Moreover, the corresponding concentration to the maximum value in step 5 is the reuse/recycle Pinch concentration (C_{pr}). Two more steps are added to traditional CTA for calculating regenerated water flow rate intervals and regeneration concentration intervals using Eq(2) and Eq(3) see Feng et al. (2007).

$$F_{reg,k} = \frac{Cum\Delta m_k - F_{fw} \times C_k}{C_k - C_0}, \forall k \to C_0 < C_k \le C_{pr} \quad (2)$$

$$C_{reg,k} = \frac{Cum\Delta m_k - F_{fw} \times C_k + F_{reg} \times C_0}{F_{reg}}, \forall k \to C_{pr} \le C_k \quad (3)$$

C_k is the concentration level determined in step 1. The largest values among $F_{reg,k}$ and $C_{reg,k}$ target the minimum regenerated water flow rate (F_{reg}) and the minimum regeneration concentration (C_{reg}).
For some networks based on the problems' characteristics, it is possible to achieve Zero Liquid Discharge (ZLD) by implementing regeneration-recycle scheme. To use the modification proposed above, the ZLD possibility should be examined first. If necessary, the limiting data will be updated before targeting the key parameters in regeneration-recycle scheme. The flowchart of improved CTA is provided in Figure 1.

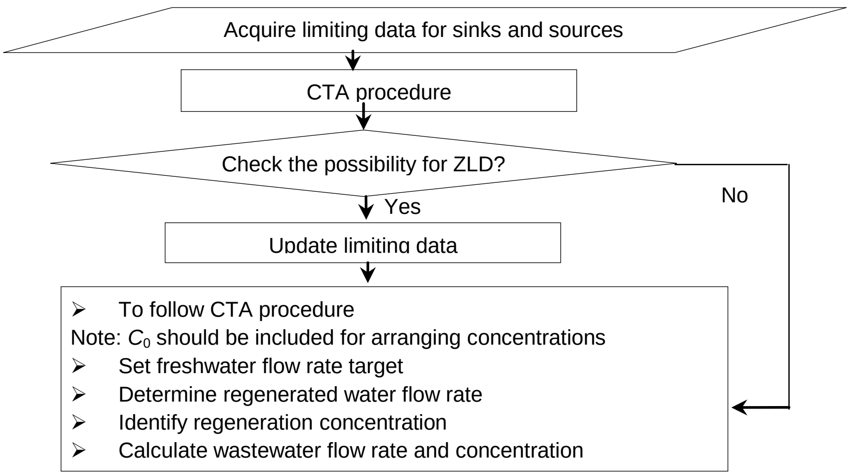

Figure 1: Flowchart for improved CTA procedure

A graphical method to target ZLD was proposed by Deng et al. (2008) and we take this graphical concept in combination with CTA to numerically target water regeneration-recycle network. If a water network encounters total water loss, there is potential to attain ZLD using regeneration unit. In this case, the inverse slope of last segment in LCC (refer to Figure 2) identifies the amount of water loss. If the freshwater flow rate can compensate the amount of water loss, the ZLD is achievable by placing the right regeneration unit. In CTA, for every concentration level (C_k), the cumulative mass load is identified. These values form the LCC. Hence, it is possible to identify the line formula for each segment of LCC. The freshwater line formula from origin parallel to the last segment of LCC is readily extractable. The intersections of freshwater line with LCC's segments below the reuse/recycle Pinch point are deduced and checked that if any of these intersections locate on any of LCC's segments. If it is affirmative, a ZLD water network is achievable. Figure 2 shows such a scenario. This intersection is named as the maximum post-regeneration concentration for ZLD network (C_{0ZLD}^{max}). The area enclosed by freshwater line and LCC is called the ZLD pocket. To utilize the improved CTA as an algebraic tool, the limiting data needs to be updated to remove the ZLD pocket.

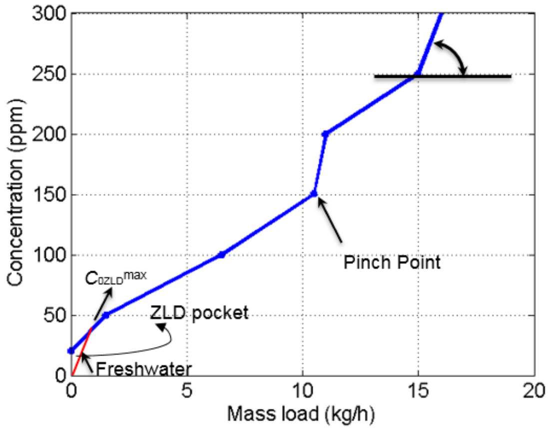

Figure 2: Schematic LCC and freshwater line for ZLD network

In the following step, it is necessary to check if there is any concentrations of sinks and sources are lower than C_{0ZLD}^{max}. Any identified concentrations should be replaced by C_{0ZLD}^{max}. This step removes all the turning points of LCC below C_{0ZLD}^{max}. A pseudo sink is added, with its concentration set a 0 ppm, and flowrate that is equal to the amount of water loss. This concentration of the pseudo sink represents the starting point of freshwater line in Figure 2. In addition, a pseudo source is also included, with flowrate equal to the amount of water loss, while its concentration takes the value of C_{0ZLD}^{max}. This value is meant for the finishing point of the freshwater line. Note that the inverse slope of the freshwater line is equal to the total flowrate loss. The described procedure for updating the limiting data removes the ZLD pocket, which enables the improved CTA to set reliable targets for both ZLD and non-ZLD networks. To elaborate this improved targeting procedure, a literature example is used for illustration.

3. Literature example

The Limiting data for a petrochemical plant (Mann and Liu, 1999) is shown in Table 1.

Table 1: Limiting data for petrochemical example

SKj	Stream	F_{SKj} (t/d)	C_{SKj} (ppm)	SRi	Stream	F_{SRi} (t/d)	C_{SRi} (ppm)
SK1	DW	360	6.0	SR1	DW	630	322.7
SK2	CT1	1,201	6.4	SR2	CT1	188	15.2
SK3	CT2	1,374	2.1	SR3	CT2	261	10.8
SK4	SC	60	20.0	SR4	SC	60	218.0
SK5	FRW	42	0.0	SR5	FRW	42	3.0

Currently, the plant consumes 3,037 t/d of fresh water, discharges 1,181 t/d of waste water, and losses a total of 1,856 t/d of water during operation. Note that this process has a mix of FL operations i.e. scrubber (SC), forward washing (FRW) and FF operations i.e. cooling towers (CT1 and CT2), Dewatering Filters (DW).

In general, regeneration unit can be characterised as either being fixed post-regeneration concentration (C_0) or fixed impurity removal ratio (Wang and Smith, 1994). In this work, it is assumed that the regeneration unit has a fixed C_0 at 2 ppm.

Since this network shows a total water loss, the ZLD possibility should be examined. Applying the proposed procedure leads to the C_{0ZLD}^{max} being targeted at 11.96 ppm. In other words, ZLD is achievable for this network when a regeneration unit with the C_0 lower than 11.96 ppm is used.

Thus, the limiting data is necessary to be modified in order to effectively apply the improved CTA as depicted in Figure 1. All concentrations lower than C_{0ZLD}^{max} are replaced by its value. A pair of pseudo sink and source is also added, with their flowrates set to that of the total water loss, i.e. 1,856 t/d. Note that the pseudo sink has a concentration of zero, while the source concentration is set to follow the C_{0ZLD}^{max} value. The updated limiting data is given in Table 2. All necessary changes to the original limiting data are shown in bold. These steams are required for the updated limiting data. Otherwise the reliable targeting for ZLD network cannot be achieved.

Table 2: Updated limiting data considering ZLD possibility

SK*j*	Stream	F_{SKj} (t/d)	C_{SKj} (ppm)	SR*i*	Stream	F_{SRi} (t/d)	C_{SRi} (ppm)
	Pseudo	**1,856**	**0**		**Pseudo**	**1,856**	**11.96**
SK1	DW	360	**11.96**	SR1	DW	630	322.7
SK2	CT1	1,201	**11.96**	SR2	CT1	188	15.2
SK3	CT2	1,374	**11.96**	SR3	CT2	261	**11.96**
SK4	SC	60	20.0	SR4	SC	60	218.0
SK5	FRW	42	**11.96**	SR5	FRW	42	**11.96**

The implementation of Improved CTA for targeting regeneration-recycle water network is demonstrated in Table 3. Two more columns are added to the traditional CTA for targeting the regenerated water flowrate (F_{reg}) and regeneration concentration (C_{reg}). The values in columns 7 and 8 are calculated via Eq(2) and Eq(3). The largest values in column 7 and 8 are the minimum targets for F_{reg} and C_{reg}. Thus, regeneration–recycle water network requires 1,856 t/d of freshwater flowrate, with the regeneration unit purifying 658.7 t/d of water from 318.13 to 2 ppm. Note that this network achieves ZLD as it experiences a total water loss of 1,856 t/h. In other words, all contaminants in the wastewater stream are being removed by the regeneration unit before they are recycled to the sinks.

Table 3: Improved CTA for targeting regeneration-recycle water network

k	C_k(ppm)	Net.F_k (t/d)	Δm_k (kg/h)	CumΔm_k (kg/h)	$F_{fw,k}$ (t/d)	$F_{reg,k}$ (t/d)	$C_{reg,k}$ (ppm)
1	0			0	0		
2	C_0=2	1,856	3.71	3.71	F_{fw}=1,856		
3	C_{0ZLD}^{max}=11.96	1,856	18.49	22.21	1,856	0	
4	15.2	2,674	8.65	30.85	2,030.1	200.5	
5	20	2,486	11.93	42.79	2,139.5	315.03	
6	C_{pr}= 218	2,546	504.11	546.90	2,508.7	F_{reg}= 658.75	218
7	322.7	2,486	260.28	807.18	2,501.3		C_{reg}=318.13
8	350	1,856	50.67	857.85	2,451		318.13

One of the valuable advantageous of this targeting method is the conversion of these algebraic targets into its graphical presentation, i.e. the LCC (Figure 3). This provides a physical insight for process engineers to design the network at later stage.

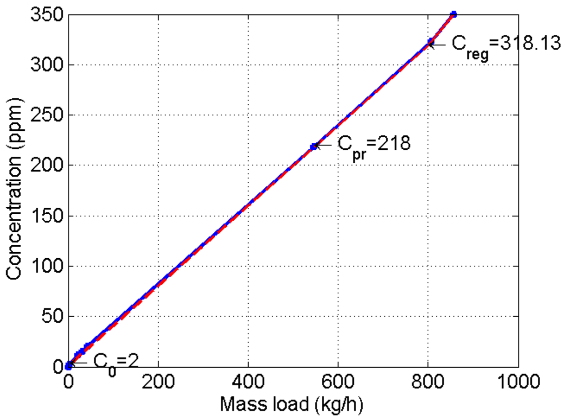

Figure 3: Targeting for petrochemical plant example (LCC shown in blue line; water supply composite shown as red line)

As depicted in Figure 3, the water supply composite curve is located entirely below the LCC and touches it in two Pinch points of 218 ppm and 322.7 ppm. Since the LCC sets the mass load feasibility boundary, this designed water supply line ensures that the targets obtained are feasible. Moreover, the formation of two Pinch points can guarantee the minimum values for the targeted parameters. However, as shown in Figure 3, the water supply composite curve and LCC are very close together. Hence, relying purely on graphical targeting tools (Agrawal and Shenoy, 2006) is not so effective and it is hard to find precise target. The magnification around the turning points of LCC is required to find the correct Pinch points and to find the rigorous targets. This task may need to be done iteratively before the reliable targets are set. Hence, this improved CTA makes the most use of the tabular tool of the CTA to obtain accurate results.

The Enhanced Nearest Neighbours Algorithm (Shenoy, 2012) is adopted to design the water network. The ZLD network is constructed using the matching matrix given in Figure 4. Note that in the design stage the original limiting data should be considered (not the updated ones). Forbidden matches across the Pinch point are shown as shaded cells. The regeneration outlet stream (Regout) should be included as a source, while its inlet (Regin) as a sink. Based on Shenoy (2012), local recycle (LR) matches should be given to FL operations in priority, then being eliminated to simplify the network structure. Scrubber is the candidate for this matter. Hence, freshwater (FW) and SR4 are used to satisfy SK4. The LR match of SR4 to SK4 is eliminated and the associated flowrates and inlet contaminant concentration are updated. All flowrate targets set earlier are achieved, proving that the pre-specified targets can be attained in practice.

		F_{SKj} (t/d)	42	1374	360	1201	~~60~~ 54.5	658.75
		C_{SKj} (ppm)	0	2.1	6	6.4	~~20~~ 0	318.13
F_{SRi} (t/d)	C_{SRi} (ppm)	SK*j* / SR*i*	SK5	SK3	SK1	SK2	SK4	Regin
1856	0	FW	42	539.74	180.99	1038.78	54.5	
658.75	2	Regout		658.75				
42	3	SR5		42				
261	10.8	SR3		133.51	127.49			
188	15.2	SR2			51.52	136.48		
~~60~~ 54.5	218	SR4				25.74	~~5.5~~ LR	28.76
630	322.7	SR1						630

Figure 4: A ZLD network for the petrochemical plant example

In comparison with the base case, freshwater consumption is saved by 39 % by implementing water regeneration-recycle network, with its wastewater generation reduced by 100 %. It is worth mentioning that the same example was studied by Mann and Liu (1999) using the concentration interval diagram, where the targets of minimum fresh water and waste water flow rate were determined as 2,318.4 and 462.4 t/d. In this work, it has been demonstrated that this network can achieve ZLD and only requires 1,856 t/d of fresh water (which is 20 % additional saving as compared to the work of Mann and Liu (1999).

As claimed, the proposed methodology has the ability to consider the entire range of C_0 as long as the problem remains feasible. To demonstrate this fact, the regeneration unit with C_0 of 20 ppm is chosen for an example. It is expected some amount of wastewater is generated with this regeneration performance because C_0 of 20 ppm is greater than C_{0ZLD}^{max}.

The implementation of improved CTA is shown in Table 4. Freshwater flow rate (F_{fw}), regenerated water flow rate (F_{reg}) and regeneration concentration (C_{reg}) are targeted as 2,139.5 t/d, 406.47 t/d and 307.24 ppm. Note that for calculating wastewater flow rate (F_{ww} = 283 t/d) and contaminant concentration (C_{ww} = 322.7 ppm), the flow rate balance and mass balance over the total system are required.

Table 4: Improved CTA for C_0 of 20 ppm

k	C_k(ppm)	Net.F_k (t/d)	Δm_k (kg/h)	Cum. Δm_k (kg/h)	$F_{fw,k}$ (t/d)	$F_{reg,k}$ (t/d)	$C_{reg,k}$ (ppm)
1	0			0	0		
2	C_{0ZLD}^{max}=11.96	1,856	22.21	22.2	1,856		
3	15.2	2,674	8.65	30.86	2,030.1		
4	C_0=20	2,486	11.93	42.79	F_{fw}=2139.5		
5	C_{pr}= 218	2,546	504.11	546.90	2,508.7	F_{reg}= 406.47	218
6	322.7	2,486	260.28	807.18	2,501.3		C_{reg}=307.24
7	350	1,856	50.67	857.85	2,451.0		288.20

Network structure is also shown in Figure 5. Wastewater (WW) is included as one of the process sinks. As demonstrated, all the flowrate targets are achieved in practice.

		F_{SKj} (t/d)	42	1,374	360	1,201	60	406.5	283.5
		$C_{SK\,j}$(ppm)	0	2.1	6	6.4	20	307.2	322.7
F_{SRi} (t/d)	C_{SRi} (ppm)	SK*j* / SR*i*	SK5	SK3	SK1	SK2	SK4	Regin	WW
2,139.5	0	FW	42	1,076.5	216.3	804.7			
42	3	SR5		42					
261	10.8	SR3		255.5	5.5				
188	15.2	SR2			138.2	49.8			
406.47	20	Regout				346.47	60		
60	218	SR4						60	
630	322.7	SR1						346.5	283.5

Figure 5: Network design for C_0 of 20 ppm

4. Conclusions

In this work, the Improved Composite Table Algorithm has been proposed for targeting regeneration-recycle water network. This method has several advantageous comparing with existing Pinch targeting techniques. It is not only able to address zero liquid discharge network based on the problem characteristic, but also provides both graphical insight and numerical accuracy at the same time. It could be improved later to relax the assumption of fixed-post regeneration concentration. The applicability of proposed method has been examined through a literature example based on a petrochemical plant.

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