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Waste Streams Identification for Water Network

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In this work, graphical and algebraic approaches are presented to identify waste streams in a water reuse/recycle network. Graphical and algebraic approaches that were originally developed for flowrate targeting are used to identify individual wastewater streams that emerge from a water reuse/recycle network. These tools supplement each other well, as graphical technique provides conceptual insights to problem analysis; while algebraic technique yields the target rapid and accurately. Literature examples are solved to illustrate the proposed approaches.

1. Introduction

Due to stringent emission legislations and the increase of waste treatment cost, waste minimisation has been a primary concern in the process and manufacturing industries. One of the active area for cost reduction activities has been that of resource conservation via in-plant material reuse/recycle, where both raw material consumption as well as the quantity of its generated waste are reduced significantly. Over the past decade, numerous research works have been performed to systematically address in-plant water reuse/recycle, covering from graphical pinch analysis techniques to mathematical-based optimisation approaches (Wang and Smith, 1994a; Hallale, 2002; El-Halwagi et al., 2003; Manan et al., 2004; Prakash and Shenoy, 2005).

Recently, Bandyopadhyay et al. (2006) proposed a new source composite curve to identify waste streams generated from a water reuse/recycle network. The identification of individual waste streams is important, as smaller waste stream flowrate leads to lower cost in the distributed waste treatment system (Wang and Smith, 1994b; Kuo and Smith, 1997). In this work, identification of individual waste streams are presented using the composite curves and cascade analysis that were developed for flowrate targeting in the water reuse/recycle network.

2. Waste Stream Identification Techniques

A novel targeting procedure is developed to identify the individual wastewater streams and their respective flowrates that are discharged from a water reuse/recycle network. Graphical and algebraic approaches that were originally developed for flowrate targeting in a reuse/recycle network are adapted here. These tools supplement each other well, as graphical technique provides conceptual insights to problem analysis; while algebraic technique yields the target rapid and accurately.

2.1 Graphical approach – material recovery pinch diagram (MRPD)

El-Halwagi et al. (2003) as well as Prakash and Shenoy (2005) individually presented the MRPD to locate the water flowrate targets for a reuse/recycle network. The MRPD is plotted on a cumulative load versus cumulative flowrate diagram such that the slopes of the segments correspond to the stream concentrations, where sink and source composite curves are individually plotted in an ascending order of the limiting concentration. Next, the source composite is moved horizontally until it touches the sink composite with the source composite being below and to the right of the sink composite curve. Minimum fresh water and wastewater targets are obtained from the overhang of the sink and source composite curves, respectively. When the water network is supplied by impure fresh water, an impure fresh locus is needed to slide the source composite curve until it touches the sink composite curve (El-Halwagi, 2006).

The composite curves in the MRPD divide the water network into two separate regions at the pinch concentration. Fresh water is used in the region having concentration lower than the pinch (lower concentration region), after the available water sources for reuse/recycle to the sinks have been exhausted. On the other hand, in the region having concentration higher than the pinch (higher concentration region), the available water sources exceed what is required by the sinks, and hence, the unused sources are discharged as wastewater. From this observation, it is noted that all wastewater streams are generated from sources in the higher concentration region. The subsequent step in the targeting procedure calls for the segregation of water sinks and sources at the pinch, followed by a new MRPD plotted for the higher concentration region. During streams segregation, all water sinks and sources are located in their respective regions, either in the higher or lower concentration regions. For the source that lies at the pinch concentration, its water allocation targets are to be identified (using targeting techniques of Hallale, 2002; El-Halwagi et al., 2003; Manan et al., 2004; Foo et al. 2006), to determine the distribution between the higher or lower concentration regions.

Water sources in the higher concentration region that emit as wastewater streams can then be identified. One of these wastewater sources will always be the pinch-causing source due to the excess of flowrate that is supplied to this region; while the other being the water source with the highest concentration. Wastewater flowrate from the pinch-causing source can be determined by deducting the minimum pinch flowrate from the allocated flowrate of the pinch-causing source to the higher concentration region. Other than that, water source(s) that is not reused/recycled to the sink(s) in this higher concentration region will be discharged as wastewater. Example 1 is used to illustrate the proposed approach.

2.1.1 Example 1

Table 1 shows the limiting data of a fixed load example consists of four sources and four sinks (Wang and Smith, 1994a). The minimum water targets for reuse/recycle case are reported as 90 t/h for both fresh water and wastewater, with the pinch concentration identified at 100 ppm (Wang and Smith, 1994a; Manan et al.,2004; Prakash and Shenoy, 2005). Figure 1 shows the MRPD for the reuse/recycle case.

After identifying the pinch concentration, the sinks and sources data are categorised into lower and higher concentration regions. The water allocation targets (Manan et al.,

Table 1 Limiting data for Example 1 (Wang and Smith, 1994a).

Sink **SK$_j$**	**Flowrate** **F_j (t/h)**	**Concentration** **C_j (ppm)**	**Sources** **SR$_i$**	**Flowrate** **F_i (t/h)**	**Concentration** **C_i (ppm)**
1	20	0	1	20	100
2	100	50	2	100	100
3	40	50	3	40	800
4	10	400	4	10	800
$\Sigma_j F_j$	170		$\Sigma_i F_i$	170	

2004) of the pinch-causing source (either SR1 or SR2 that are located at 100 ppm), correspond to 70 t/h that is sent to the lower concentration region ($F_{\mathrm{L,\ pinch}}$) and 50 t/h to the higher concentration region ($F_{\mathrm{H,\ pinch}}$), has also been included in their respective regions. The segregation of the water sinks and sources leads to SK4, SR3 and SR4 (the pinch-causing source is omitted) being allocated to the higher concentration region. The new MRPD plotted for this region is shown in Figure 2. As shown, the minimum pinch flowrate (F_{pinch}) is targeted as 5.71 t/h.

The individual wastewater streams from the higher concentration region can now be determined. The wastewater flowrate from the pinch concentration corresponds to the difference between the minimum pinch flowrate (5.71 t/h) and the allocated flowrate of the pinch-causing source to the higher concentration region (50 t/h), i.e. 44.29 t/h. Figure 2 also shows that 45.71 t/h of wastewater is emitted from the highest concentration sources at 800 ppm (i.e. SR3 and SR4). One can easily verify the total

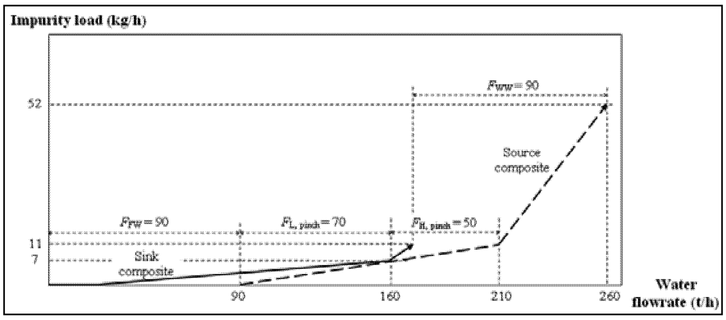

Figure 1 MRPD for Example 1 (reuse/recycle network).

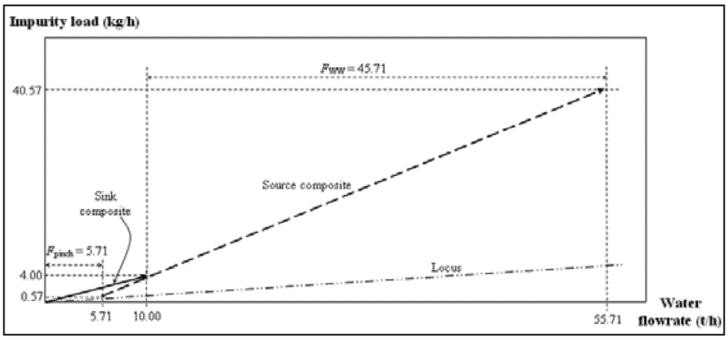

Figure 2 MRPD for higher concentration region (Example 1).

wastewater flowrate by summing the individual wastewater streams (44.29 t/h + 45.71 t/h = 90 t/h), which matches exactly the overall wastewater target identified in Figure 1.

2.2 Algebraic approach – Water Cascade Analysis (WCA)

In this section, the WCA technique that was developed to target the minimum flowrates for a reuse/recycle network (Manan et al, 2004; Foo et al., 2006) is revised to identify flowrate of the individual wastewater streams.

The overall concept to identify the individual wastewater flowrate using the WCA is similar to that of the graphical technique, with the first step being to locate the minimum flowrates and pinch concentration of the water reuse/recycle network. Next, the water sources and sinks are segregated into the lower and higher concentration regions. This includes the allocated flowrates of the pinch-causing source that are identified from the WCT, i.e. concentration intervals just above and below the pinch in the F_C column. (Manan *et* al, 2004; Foo et al., 2006). Next, a new WCA is conducted for the higher concentration region to locate the minimum pinch flowrate, $F_{PW,k}$, via the modified Equation 3.1 as follow:

$$F_{\mathrm{PW},k} = \frac{\mathrm{Cum.}\Delta \mathrm{m}_k}{C_k - C_{\mathrm{pinch}}} \tag{1}$$

where C_{pinch} = pinch concentration. Similar to the case of graphical targeting, the allocated flowrate of the pinch-causing source is omitted in the pinch flowrate targeting in this higher concentration region. The pinch flowrate target is the minimum flowrate requirement (supplied at the pinch concentration) to satisfy all water sinks in the higher concentration region.

As in the case of the graphical targeting, the difference between the minimum pinch flowrate and the allocated flowrate of the pinch-causing source to the higher concentration region gives the wastewater generated at the pinch concentration. Besides, the unused source in this region will discharge as wastewater. Example 2 will be used to demonstrate the algebraic targeting approach.

2.2.1 Example 2

Table 2 shows the limiting data of a fixed flowrate example from Sorin and Bédard (1999). The minimum water targets for reuse/recycle are firstly determined by WCA (Table 3) to be 200 t/h fresh water (F_{FW}) and 120 t/h wastewater (F_{WW}), while 100 ppm and 180 ppm are identified as pinch concentrations (Hallale, 2002; Manan et al., 2004). From Table 3, it is noted that there are two pinch concentrations (100 ppm and 180 ppm) in the network and these pinch concentrations separate the water sinks and sources into three different regions i.e. region with excess of water (higher concentration than the upper pinch), region of self-sustained (between the lower and upper pinches) and region with water deficit (lower concentration than the lower pinch). Hence, the wastewater is expected to originate from the region with excess water. Note that, Table 3 also shows the allocation flowrates of the upper pinch-causing source, where 100 t/h is sent to region between the pinch points, which is self-sufficient in terms of water demand, while 40 t/h of water is sent to region with excess water (intervals just above and below 180 ppm in column F_C) (Sorin and Bédard, 1999).

Next, water sinks and sources are segregated into different regions. Sinks SK1, SK2 and SK3 and a portion of source SR1 (80 t/h) are allocated to the region with water deficit. Sinks SK4, SK5 as well as sources SR2 and portion of SR1 (40 t/h) and SR4 (100 t/h) are allocated to the middle region between the pinch points. Besides, sinks SK6 and sources SR5 and SR6 (pinch-causing source SR4 is omitted) which have higher concentration than the upper pinch concentration (180 ppm) are allocated to

Table 2 Limiting data for Example 2 (Sorin and Bédard, 1999).

Sinks SK$_j$	Flowrate F_j (t/h)	Concentration C_j (ppm)	Sources SR$_i$	Flowrate F_i (t/h)	Concentration C_i (ppm)
1	120	0	1	120	100
2	80	50	2	80	140
3	80	50	3	-	-
4	140	140	4	140	180
5	80	170	5	80	230
6	195	240	6	195	250
ΣF_j	695		ΣF_i	615	

Table 3 WCA targeting for water reuse/recycle case (Example 2).

k	C	ΣF_j	ΣF_i	$\Sigma F_i - \Sigma F_j$	F_C	Δm_k	Cum Δm_k	$F_{FW,k}$	F_C	Δm_k	Cum Δm_k
					0				**$F_{FW} = 200$**		
1	0	120		-120							
					-120	-6			80	4	
2	50	160		-160			-6	-120.00			4.00
					-280	-14			-80	-4	
3	100		120	120			-20	-200.00			**0.00**
					-160	-6.4			40	1.6	(LOWER PINCH)
4	140	140	80	-60			-26.4	-188.57			1.60
					-220	-6.6			-20	-0.6	
5	170	80		-80			-33	-194.12			1.00
					-300	-3			-100	-1	
6	180		140	140			-36	-200.00			**0.00**
					-160	-8			40	2	(UPPER PINCH)
7	230		80	80			-44	-191.30			2.00
					-80	-0.8			120	1.2	
8	240	195		-195			-44.8	-186.67			3.20
					-275	-2.75			-75	-0.75	
9	250		195	195			-47.55	-190.20			2.45
					-80	-79980			**$F_{WW} = 120$**	119970	
10	1000000						-80027.55	-80.03			119972.45

Table 4 Waste stream identification for region with higher concentration than upper pinch (Example 2).

k	C	ΣF_j	ΣF_i	$\Sigma F_i - \Sigma F_j$	F_C	Δm_k	Cum Δm_k	$F_{FW,k}$	F_C	Δm_k	Cum Δm_k
					0				**$F_{PW} = 5$**		
1	180			0							
					0	0			5	0.25	
2	230		80	80			0	0.00			0.25
					80	0.8			85	0.85	
3	240	195		-195			0.8	13.33			1.10
					-115	**-1.15**			**-110**	**-1.1**	
4	250		195	195			-0.35	-5.00			**0.00**
					80	79980			**85**	84978.75	(PINCH)
5	1000000						79979.65	79.99			84978.75

region with excess of water. A new WCA is conducted for the region with excess water to determine the individual wastewater streams that are emitted, with an impure fresh feed at 180 ppm (upper pinch concentration).

As shown in Table 4, the minimum pinch flowrate (F_{PW}) is determined as 5 t/h; while 85 t/h of wastewater is emitted from the final concentration level of 250 ppm. As stated earlier that 40 t/h of the upper pinch-causing source (180 ppm) is supplied to this region. Hence, the wastewater that will be emitted from the upper pinch (180 ppm) for treatment is determined as 35 t/h. Summing the individual wastewater streams from the upper pinch as well as the highest concentration source yield the total wastewater flowrate of 120 t/h,which matches the overall wastewater target (refer to Table 3).

3. Conclusion

Graphical and algebraic approaches for waste stream identification are presented in this work. Prior to detailed network design, the technique enables the designer to identify individual waste streams to be treated in a decentralised waste treatment facility.

4. Acknowledgement

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