Reply:

For the total water network example considered by Foo (Letter to the Editor, DOI 12304, AIChE J. 2010; 56(9):2492–2494), it is demonstrated later that the proper application of the composite table algorithm (CTA)[1] for targeting followed by the nearest neighbors algorithm (NNA)[1,2] for network design allows the synthesis of optimum resource conservation networks (RCNs) that achieve minimum flow rates even with interception placement. The inlet streams to interception units (i.e., regeneration units and waste treatment units) are considered as demands (or sinks), whereas the outlet streams from interception units are regarded as sources. Importantly, the NNA being a network design tool should be applied only after targets are accurately and completely established in terms of both flow rates and contaminant concentrations for resource (freshwater), waste (wastewater), and streams associated with interception units.

The notation throughout is very similar to that used by Agrawal and Shenoy[1] with a few minor exceptions as indicated later. The RCNs are presented in terms of matching matrices[3] because this representation is compact and is also helpful in the evolution of networks.[4]

Total water network example

The example deals with a classical water minimization problem whose limiting water data are given by Wang and Smith.[5] The original fixed contaminant load problem, however, is modified by Foo (2010) to include two interception units, one for regeneration with a fixed outlet concentration $C_o = 5$ ppm, and another for wastewater treatment with an outlet concentration $C_{tout} = 10$ ppm. Furthermore, the environmental discharge limit is specified as $C_{ww} = 20$ ppm. Here, the fresh resource is specified as freshwater (WS) with $C_{ws} = 0$ ppm. For this example of a concentration-based total water network with two interception units (each with a single inlet and a single outlet), the targets are first established by the CTA along with fundamental balance equations. Networks are then designed by the NNA to achieve these targets.

Targeting

The implementation of the CTA[1] on the limiting water data comprising four water-using processes (equivalent to four demands and four sources) is shown in Table 1. The concentration may be plotted against the cumulative load (first column vs. fourth column in Table 1) to obtain the limiting water composite curve[1] (not shown for brevity). The maximum value (90 t/h) in the last column specifies the pinch, which corresponds to $C_p = 100$ ppm and $m_p = 9$ kg/h.

This pinch point information may be utilized with the following system of equations (analogous to equations originally proposed by Agrawal and Shenoy[1] for water and hydrogen systems) to establish the necessary targets for a concentration-based total water network with a regeneration process and a wastewater treatment process

$$F_{ws} - F_{ww} = \Delta_1 \quad \text{where } \Delta_1 \equiv \sum F_d - \sum F_s \qquad (1)$$

$$F_{ws}C_{ws} - F_{ww}C_{ww} = \Delta_2 + F_{reg}(C_{in} - C_o) + F_t(C_{tin} - C_{tout}) \quad \text{where } \Delta_2 \equiv \sum F_d C_d - \sum F_s C_s \qquad (2)$$

$$m_p = F_{ws}(C_p - C_{ws}) + F_{reg}(C_p - C_o) \qquad (3)$$

$$F_{ww}(C_p - C_{ww}) = F_t(C_p - C_{tout}) \qquad (4)$$

Equations 1 and 2 are mass balances for water and contaminant over the total system. Equation 2 considers the inlet streams to the regeneration and wastewater treatment units as two demands and the outlet streams from the regeneration and treatment units as two sources. Equation 3 is the mass balance over the below-pinch region of the limiting water composite curve,[1] which provides the net demand of the system and requires profile matching with the freshwater line. In an analogous manner, Eq. 4 is the simplified mass balance over the below-pinch region of the source composite curve,[6] which provides the net source of the system and requires profile matching with the wastewater and treatment lines. Equation 3 holds for a regeneration process starting at or above the pinch concentration C_p, and achieving an outlet concentration of C_o, whereas Eq. 4 additionally holds for a treatment process starting at or above the pinch concentration C_p, and achieving an outlet concentration of C_{tout}. For this example, the pinch occurs at $C_p = 100$ ppm for the limiting water composite and the source composite (with the two curves being reflections of each other in a vertical mirror). As an aside, note that Agrawal and Shenoy[1] solved a similar system of three equations (without Eq. 4) for regeneration networks without wastewater treatment. The system requires an extra equation for each additional pinch point for special multipinch cases.[7] The net system flow rate (Δ_1), and the net system load (Δ_2) are constant for a given problem ($\Delta_1 = 0$ t/h and $\Delta_2 = -41$ kg/h for this example).

Since the system comprises four equations in six unknowns (F_{ws}, F_{ww}, F_{reg}, F_t, C_{in}, and C_{tin}), there are two degrees of freedom. So, two variables need to be specified to solve the equations and determine the targets. The freshwater requirement and consequently the wastewater generation can be reduced to the absolute minimum through regeneration with recycle according to Wang and Smith.[5] In this case, the slope of the limiting composite below C_o sets the minimum freshwater flow rate. For this example, the freshwater flow rate required is 20 t/h as per Table 1. Equation 1, thus, gives the absolute minimum freshwater and wastewater targets as $F_{ws} = F_{ww} = 20$ t/h. Substituting these values for F_{ws} and F_{ww} in Eqs. 3 and 4, respectively, the targets for the flow rates through the regeneration and treatment units are $F_{reg} = [9 \times 10^3 - 20(100 - 0)]/(100 - 5) = 73.684$ t/h and $F_t = 20(100 - 20)/(100 - 10) = 17.778$ t/h. Finally, Eq. 2 gives $73.684\, C_{in} + 17.778\, C_{tin} = 41146.2$, indicating that there are many different pairs of C_{in} and C_{tin} values that satisfy this equation. For instance, (379.2 ppm, 742.8 ppm), (534.286 ppm, 100 ppm) and (365.397 ppm, 800 ppm) are three pairs of values for (C_{in}, C_{tin}) that satisfy the equation,

Table 1. Implementation of Composite Table Algorithm (CTA) for Example

Contaminant Concentration C (ppm)	Net Flow rate (t/h)	Net Load (kg/h)	Cumulative Load m_{cum} (kg/h)	$m_{cum}/(C - C_{ws})$ (t/h)
0			0	
50	20	1	1	20
100	160	8	**9**	**90**
400	40	12	21	52.5
800	50	20	41	51.25
(1000)	0	(0)	(41)	41

AIChE Journal, Vol. 57, 1096–1098 (2011)

DOI 10.1002/aic.12583
Published online March 4, 2011 in Wiley Online Library (wileyonlinelibrary.com).

F t/h		20	100	40	10	73.684	17.778	20
{C ppm}		{0}	{50}	{50}	{400}	{379.2}	{742.8}	{20}
		SK1	SK2	SK3	SK4	RIN	TIN	WW
20 {0}	WS	20						
73.684 {5}	REG		52.632	21.053				
20 {100}	SR1		20					
100 {100}	SR2		27.368	18.947	5.714	44.295	1.453	2.222
40 {800}	SR3				4.286	29.389	6.325	
10 {800}	SR4						10	
17.778 {10}	TOUT							17.778

(a)

F t/h		20	100	40	10	73.684	17.778	20
{C ppm}		{0}	{50}	{50}	{400}	{534.3}	{100}	{20}
		SK1	SK2	SK3	SK4	RIN	TIN	WW
20 {0}	WS	20						
73.684 {5}	REG		52.632	21.053				
20 {100}	SR1		1.053	18.947				
100 {100}	SR2		46.315		5.714	27.97	17.778	2.222
40 {800}	SR3					40		
10 {800}	SR4				4.286	5.714		
17.778 {10}	TOUT							17.778

(b)

F t/h		20	100	40	10	73.684	17.778	20
{C ppm}		{0}	{50}	{50}	{400}	{365.4}	{800}	{20}
		SK1	SK2	SK3	SK4	RIN	TIN	WW
20 {0}	WS	20						
73.684 {5}	REG		52.632	21.053				
20 {100}	SR1		20					
100 {100}	SR2		27.368	18.947	5.714	45.747		2.222
40 {800}	SR3					22.222	17.778	
10 {800}	SR4				4.286	5.714		
17.778 {10}	TOUT							17.778

(c)

Figure 1. Network designs for example by NNA.

with the first pair of values being those used by Foo (2010) in Figure 3. In the next subsection, three different networks are designed by the NNA for these three pairs of values, with all three networks achieving the minimum flow rate targets for freshwater ($F_{ws} = 20$ t/h), wastewater ($F_{ww} = 20$ t/h), regenerated water ($F_{reg} = 73.684$ t/h) and treated water ($F_t = 17.778$ t/h).

Network design

In general, the targets may be achieved in practice through many different network designs. Several networks (shown as matching matrices in Figure 1), all satisfying the minimum flow rate targets, may be synthesized using the NNA depending on the order in which the demands are satisfied. Note that it is convenient to arrange the sources in ascending (or descending) order of quality level in order to readily identify the nearest neighbors; however, it is not necessary (although often convenient) to arrange the demands because they can be satisfied in any order.[1] Arranging demands in order of quality nevertheless provides the convenience of identifying the cross-pinch regions (grayed in Figure 1).

In Figure 1a, demand SK1 is first satisfied by freshwater WS of the same concentration (zero contaminant). According to the principle of nearest neighbors, demand SK2 at 50 ppm is satisfied by the nearest neighbor sources at 5 ppm and 100 ppm. By material balance equations, 100 t/h of demand SK2 require 52.632 t/h of 5 ppm source (regenerated water REG), and 47.368 t/h of 100 ppm sources (20 t/h of SR1 and 27.368 t/h of SR2). Similarly, demand SK3 (40 t/h at 50 ppm) is satisfied by the remainder of regenerated water REG (21.053 t/h at 5 ppm), and source SR2 (18.947 t/h at 100 ppm). Now, the nearest neighbors to demands SK4 (400 ppm), RIN (379.2 ppm) and TIN (742.8 ppm) are sources at 100 and 800 ppm. So, 10 t/h of demand SK4 are satisfied by 5.714 t/h of 100 ppm source (SR2) and 4.286 t/h of 800 ppm source (SR3). Next, 73.684 t/h of demand RIN (inlet to regenerator) are satisfied by 44.295 t/h of 100 ppm source (SR2) and 29.389 t/h of 800 ppm source (SR3). Then, 17.778 t/h of demand TIN (inlet to treatment unit) are satisfied by 1.453 t/h of 100 ppm source (SR2) and 16.325 t/h of 800 ppm sources (6.325 t/h of SR3 and 10 t/h of SR4). Finally, the remainder of source SR2 (2.222 t/h at 100 ppm), and the outlet of the treatment unit TOUT (17.778 t/h at 10 ppm) are discharged as wastewater WW (20 t/h at 20 ppm). The network achieves the targets, and shows no cross-pinch transfer (as indicated by the fact that there are no matches in the grayed cells of the matching matrix in Figure 1a).

Three possible networks are shown in Figure 1 corresponding to the three different pairs of (C_{in}, C_{tin}) values calculated earlier. The demands are satisfied by a straightforward application of the NNA in the sequential order of SK1, SK2, SK3, SK4, RIN, TIN and WW (Figure 1a), then in the order of RIN, SK4, TIN, WW, SK3, SK2, and SK1 (Figure 1b), and finally in the order of TIN, RIN, SK4, WW, SK2, SK3, and SK1 (Figure 1c). Figure 1a is essentially the network reported in Figure 3 by Foo (2010), and features one extra match compared to the networks in Figures 1b and 1c. The three networks although structurally different are conceptually similar for this example because several sources and demands have the same contaminant concentration (e.g., SR1 and SR2 are at 100 ppm, SR3 and SR4 are at 800 ppm, SK2 and SK3 are at 50 ppm); therefore, there are actually only two possible below-pinch designs.

Conclusion

The nearest neighbors algorithm (NNA) is a powerful yet simple design tool to synthesize optimal RCNs that satisfy the targets for all types of resource allocation problems including complicated ones with interception placement. Importantly, proper and successful application of the NNA requires that the targeting be accurately and rigorously completed; in other words, NNA should be applied only after the flow rates and contaminant concentrations for all possible sources and demands (including freshwater, wastewater, and streams associated with interception units) are known. Network design (by NNA) is an independent stage provided accurate targets are completely established *a priori*, which is consistent with the original philosophy of pinch analysis. It must be emphasized that the NNA is a network design tool and not a targeting tool. The CTA, along with the limiting water composite and source composite curves, supplemented by fundamental balance equations provides an accurate and rigorous targeting tool to determine the optimal requirements for external resource, waste generation, flows of the regeneration unit, and effluent treatment to meet environmental norms.

The NNA does not require demands to be arranged in order of quality levels. It is possible to have multiple optimum RCNs;[8] thus, many networks, all of which satisfy the targets, can be synthesized using the NNA depending on the order in which the demands are satisfied.

Literature Cited

1. Agrawal V, Shenoy UV. Unified conceptual approach to targeting and design of water and hydrogen networks. *AIChE J*. 2006; 52(3):1071–1082.
2. Prakash R, Shenoy UV. Targeting and design of water networks for fixed flow rate and fixed contaminant load operations. *Chem Eng Sci*. 2005;60(1):255–268.
3. Prakash R, Shenoy UV. Design and evolution of water networks by source shifts. *Chem Eng Sci*. 2005;60:2089–2093.
4. Das AK, Shenoy UV, Bandyopadhyay S. Evolution of resource allocation networks. *Ind Eng Chem Res*. 2009;48:7152–7167.
5. Wang YP, Smith R. Wastewater minimization. *Chem Eng Sci*. 1994;49:981–1006.
6. Bandyopadhyay S. Source composite curve for waste reduction. *Chem Eng J*. 2006;125: 99–110.
7. Agrawal V, Shenoy UV. Letter to the editor. *AIChE J*. 2007;53(11):3017.
8. Pillai HK, Bandyopadhyay S. A rigorous targeting algorithm for resource allocation networks. *Chem Eng Sci*. 2007;62:6212–6221.

Uday V. Shenoy
Synew Technologies, A 502 Galleria
Hiranandani Gardens, Powai
Mumbai 400076, India
E-mail: shenoys@vsnl.com

Santanu Bandyopadhyay
Gopal Chandra Sahu
Dept. of Energy Science and Engineering
Indian Institute of Technology, Bombay, Powai
Mumbai 400076, India
E-mail: santanu@me.iitb.ac.in
E-mail: gopalch@iitb.ac.in