Evolution of Water Network Using Improved Source Shift Algorithm and Water Path Analysis

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An improved source shift algorithm (SSA) and water path analysis (WPA) is proposed in this work to evolve a preliminary water network. The earlier version of SSA, which reduces the complexity of a preliminary water network, is iterative in nature and involves trial-and-error solution. The improved SSA proposed in this work is noniterative and is able to evolve the preliminary water network while maintaining its minimum freshwater and wastewater flow rates. Moreover, the WPA is used to shift the water loads along a water path to reduce the number of interconnections by incurring a penalty on both freshwater and wastewater flow rates. Three literature examples are solved to illustrate the applicability of the developed methods.

Introduction

The exhaustion of natural resources will soon become the major problem for the world. The fact that the world faces a water crisis recently has become increasingly clear. Challenges remain widespread and reflect severe problems in the management of water resources in many parts of the world. These problems will intensify unless effective and concerted actions are taken, as is made in the World Water Vision.[1]

Apart from that, the increase of public awareness about environmental issue, the higher cost of raw materials, and stringent emission legislations have forced the process industries to look into cost-effective measures to reduce production and treatment costs, to ensure business competitiveness. One of the active areas for cost reduction activities has been that of in-plant material reuse/recycle, with the most active area being the water network synthesis. Various research works have been conducted to systematically address in-plant water reuse/recycle in the past decade, covering methodologies from graphical pinch analysis to mathematical-based approaches. Examples of these research efforts can be found in the literature.[2−20]

In the area of graphical pinch analysis, various minimum water flow rate targeting techniques have been introduced (e.g., limiting water profile,[2] water surplus diagram,[11] material recovery pinch diagram,[12,14] and water cascade analysis[13,18]). Besides, numerous water network design techniques have also been developed to assist designers to synthesize a water network that achieves the minimum water targets.[2,10,14,15,17,19,22] One of the promising techniques for synthesizing a water network for fixed-flow-rate (also called non-mass-transfer-based[11,13]) processes is the nearest-neighbors algorithm (NNA).[14] A preliminary water network that is designed using NNA can be further simplified with a source shift algorithm (SSA).[15] However, the SSA[15] is iterative in nature and requires time-consuming trial-and-error solution. Further work is needed to improve this algorithm, and this is the subject of this paper.

This paper first proposes an improved SSA to evolve the preliminary network. With the new guideline proposed in this work, a simpler water network can be obtained without tedious iteration. Next, a novel concept of water path analysis is introduced to allow the designer to reduce the number of interconnections systematically and quickly, at the cost of a freshwater penalty.

Concept of NNA and SSA

The basic principle of NAA in its simplest form may be stated as follows: "*To satisfy a particular water sink, the sources to be chosen are the nearest available neighbors to the sink in terms of contaminant concentration*".[14] In other words, a source that is just cleaner than a sink is mixed with a source that is just dirtier than the sink to satisfy the flow rate and load requirements of the sink. In this case, the required amounts of the two neighbor sources are dictated by the material balance equations. If the required flow rate of a source is not sufficient, then the total flow rate of that source is used completely and the next neighbor source is considered to satisfy the sink.[14]

The NNA generates a single network that meets the minimum water targets. However, there may be many alternative networks, all of which may satisfy the minimum water targets. In cases where a different network design is needed, because of process constraints (e.g., geographical, operation, and maintenance), SSA can be used to generate different network configurations.[15] Using SSA, the water source is moved from one sink to another without affecting the flow rate and contaminant concentration of either sink. This can be achieved by mixing the different sources to fulfill the sink requirements in the network. Therefore, various alternative networks can be obtained. Moreover, SSA can also be used to remove one or more interconnections in a preliminary network and, hence, a less-complex network may be obtained.[15] However, the earlier version of SSA[15] is tedious and cumbersome, because of its iteration nature. In this work, new guidelines are presented to improve the algorithm, in regard to reducing the number of interconnections in a preliminary water network.

Guidelines for Noniterative Improved SSA

The new guidelines presented in this section will enable the improved SSA to eliminate the number of interconnections in a preliminary network without trial-and-error iteration, while maintaining the minimum water flow rates. Because the SSA involves the movement of a few water sinks and sources, these candidates are to be identified in the first step. Two main criteria to consider the water sink and source candidates in the improved SSA are given as follows:

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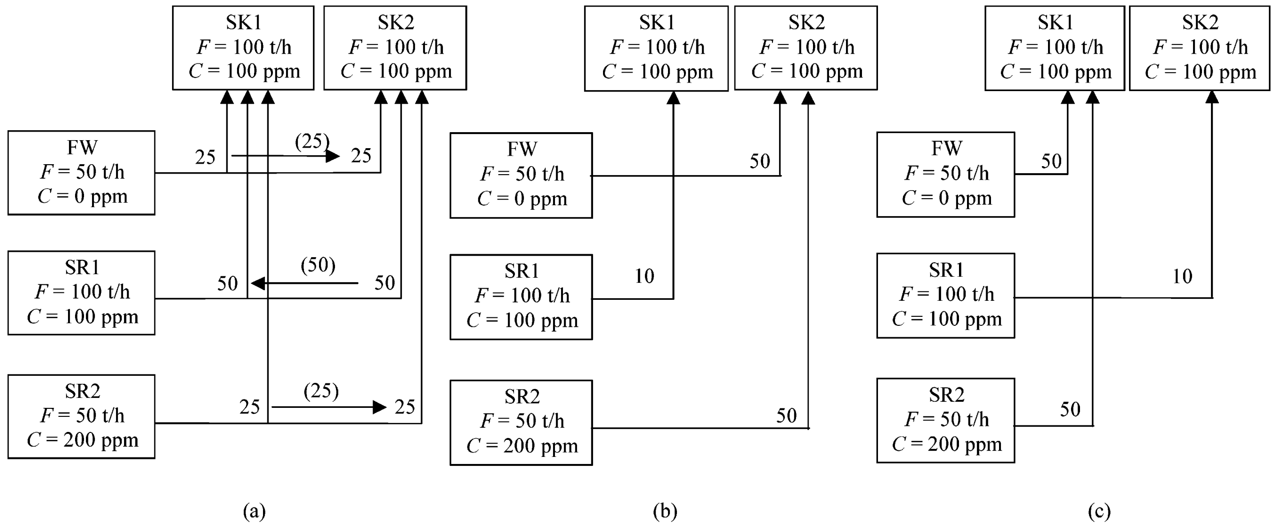

Figure 1. Multiple-point shifts using improved source shift algorithm (SSA): (a) six interconnections before source shift operation; (b) three interconnections are removed simultaneously; (c) alternative network configuration by performing the source shift in the reverse direction.

(1) Both the sink and the source should have the same level of concentration.

(2) The flow rate of the source should be higher than, or equal to, that of the sink.

Hence, for a given preliminary water network (e.g., synthesized from NNA), the water sink and source with the same concentration level are first identified. Next, a source candidate with a flow rate higher than or equal to its corresponding sink candidate (at the same concentration level) is selected. Note that this flow rate constraint is an important criterion, because the elimination of an interconnection will not be achieved if the selected source has a smaller flow rate than that of the sink (because of the transfer of another source to satisfy the need of the sink flow rate). Next, the sink candidate will be fully supplied by the selected source candidate. However, moving the source candidate flow rate to the sink candidate indicates that the original sink that was originally supplied by the source candidate is experiencing a flow rate deficit. Hence, an equal flow rate from two or more water sources that were originally supplying the sink candidate will have to be shifted to the corresponding sink, which is experiencing a flow rate deficit. In this case, multiple point shifts are performed. The main criterion to be taken into account in the multiple point shifts is that an equal amount of water flow rate must be shifted between the matches to ensure the water flow rate balance in the various sink−source matches. This algorithm is not restricted to only a three-point shift, as proposed by Prakash and Shenoy.[15]

With this improved SSA, two or more interconnections may be simultaneously eliminated in some networks. Also, when there is more than one sink candidate to perform the SSA, the designer possesses more flexibility and has more alternatives in regard to evolving the network. Alternative network designs are useful when topological and other process constraints are to be incorporated during network synthesis. Figure 1 illustrates such a situation. As shown, there are one source and two sinks that serve as the candidates for SSA. One alternative to evolve the network is to shift 50 t/h of water from the SK2−SR1 match to the SK1−SR1 match. An equal amount of water flow rate is then shifted from the SK1−FW and SK1−SR2 matches to the SK2−FW and SK2−SR2 matches, respectively (see Figure 1a). These source shifts remove the three interconnections simultaneously (Figure 1b). It is interesting to note that, because the water sinks have the same concentration, one may also evolve the network to a different configuration by performing the source shifts in a reverse direction (see Figure 1c).

Table 1. Limiting Data for Example 1[a]

Sinks			Sources		
SK*j*	flow rate, F_j (t/h)	concentration, C_j (ppm)	SR*i*	flow rate, F_i (t/h)	concentration, C_i (ppm)
SK1	50	20	SR1	50	50
SK2	100	50	SR2	100	100
SK3	80	100	SR3	70	150
SK4	70	200	SR4	60	250
$\Sigma_j F_j$	**300**		$\Sigma_i F_i$	**280**	

[a] Data taken from ref 5.

Note that, in the original work of Prakash and Shenoy,[15] iterative steps are needed to achieve the elimination of an interconnection. With the proposed criteria in this work, the iteration needs are eliminated and the network can be evolved more efficiently. Two literature examples are used to demonstrate the new guidelines.

Example 1. Table 1 shows the limiting data of a fixed-flow-rate example taken from Polley and Polley,[5] which was comprised of four sources and four sinks. The minimum freshwater and wastewater flow rates were targeted prior to network design to be 70 and 50 t/h, respectively, with 150 ppm identified as a pinch concentration.[11−14,20]

Prakash and Shenoy[15] showed that the water network (Figure 2) generated using the NNA may be conveniently represented as a matching matrix (Table 2), where water sources *i* (SR*i*) appear as rows and sink *j* (SK*j*) as columns, arranged in an increasing order of concentration. The first row of the matching matrix with 0 ppm indicates a freshwater (FW) source, whereas the last column of the matching matrix indicates wastewater (WW). As shown, the water network that fulfills the minimum water flow rates features a total of 12 interconnections among the water sinks and sources.

As reported by Prakash and Shenoy,[15] several iterative trials are needed to eliminate an interconnection from the water network. These iterative trials can be readily avoided using the improved SSA proposed in this work. Following the aforementioned procedure, water sinks and sources with the same concentration level are first identified. In this example, two sink−source pairs with the same concentration level are identified (i.e., SR1 with SK2 (50 ppm) and SR2 with SK3 (100

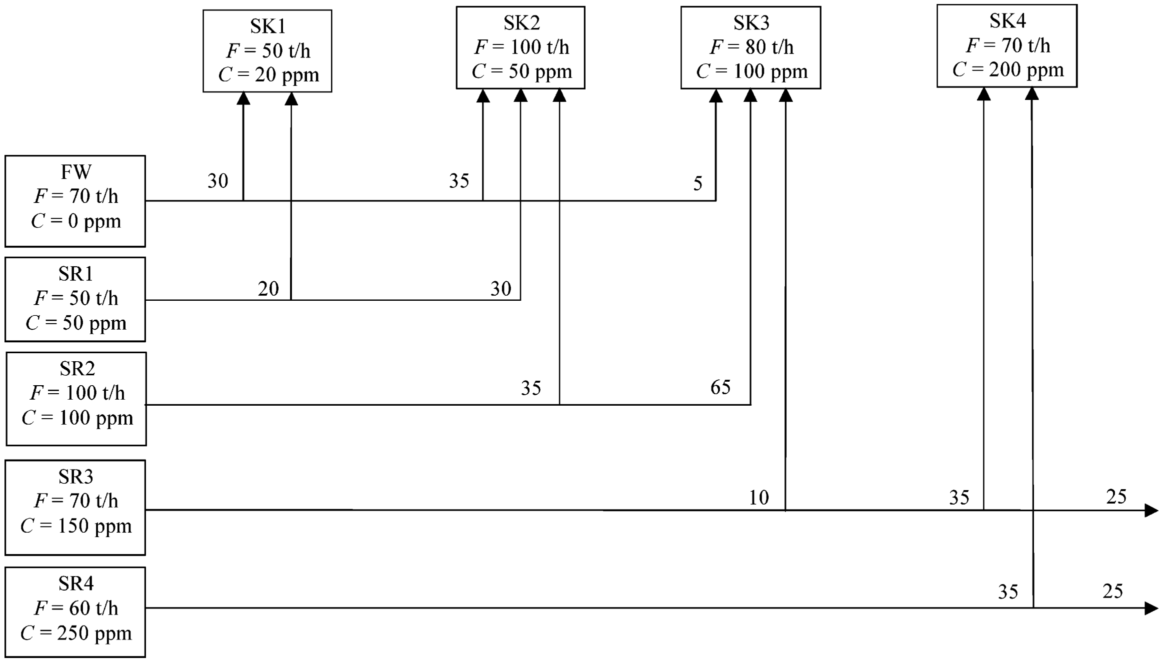

Figure 2. Minimum water network for Example 1, designed by the nearest-neighbors algoritm (NNA) (the number that appear above the reuse/recycle streams indicate the flow rates, given in units of t/h).[15]

Table 2. Network Design Represented as Matching Matrices for Example 1

		***F**$_j$* **(t/h)**	50	100	80	70	50
		***C**$_j$* **(ppm)**	20	50	100	200	
***F**$_i$* **(t/h)**	***C**$_i$* **(ppm)**	**SK*j*** / **SR*i***	SK1	SK2	SK3	SK4	WW
70	0	FW	30	35	5		
50	50	SR1	20	30			
100	100	SR2		35	65		
70	150	SR3			10	35	25
60	250	SR4				35	25

ppm)). However, only the SR2−SK3 match complies with the second criteria, (i.e., SR2 has a higher flow rate than SK3) and, hence, is considered for network evolution.

Upon the identification of the right sink−source candidates, source shift operation can now be performed. As a start, sink SK3, which requires a water flow of 80 t/h, will be fully supplied by source SR2. An equal amount of water flow is shifted from SK3 to SK2 via the SK2−FW (5 t/h) and SR3−SK_2 (10 t/h) matches. The result after the source shift is shown in Table 3. As shown, two interconnections (i.e., the SK3−FW and SK3−SR3 matches) are eliminated and a new SK2−SR3 match emerges. The overall result is an evolved network with 11 matches, i.e., one interconnection less than the preliminary network in Table 2. Hence, a simpler network is produced which matches the earlier finding[15] but in a more-efficient way.

Example 2. To illustrate the multiple point shifts in the improved SSA, another water network with fixed-load water-using processes is considered. The limiting data for Example 2, which consists of 10 water sinks and 10 water sources, are given in Table 4.[8,9] The minimum water flow rates for this example may be targeted by composite curves[2,12,14] or a numerical method[9,13] as 166.27 t/h for both freshwater and wastewater, with a pinch concentration located at 300 ppm. Based on NNA, the preliminary water network was designed and is represented by a matching matrix in Table 5.

From Table 5, one can observe that there is only one pair of sink-source match that satisfies both the criteria of the improved SSA, i.e., source SR3 and sink SK7. Both sink and source are having a concentration of 200 ppm and source SR3 has a higher flow rate than sink SK7. Therefore, the source shift operation can be carried out to eliminate interconnection from the preliminary water network.

In this case, multiple point shifts are needed to evolve the network. As shown in Table 5, sink SK7 which needs 5 t/h of 200 ppm water is fully satisfied by source SR3 (3.81 t/h). Next, 0.323 t/h of freshwater (FW), 1.42 t/h of 100 ppm water (SR4) and 2.067 t/h of 300 ppm water (SR9) are shifted to sink SK10. The evolved network is shown in Table 6 and the one interconnection (i.e. SK7−SR4) has been removed from the original design (Table 5).

Water Path Analysis

Water path analysis (WPA) is a newly proposed concept. It is a noniterative method that allows the designer to eliminate

Table 3. Network Design Represented as Matching Matrices after the Source Shifts between SK2 and SK3

		F_j (t/h)	50	100	80	70	50
		C_j (ppm)	20	50	100	200	
F_i (t/h)	C_i (ppm)	SR*i* \ SK*j*	SK1	SK2	SK3	SK4	WW
70	0	FW	30	40			
50	50	SR1	20	30			
100	100	SR2		20	80		
70	150	SR3		10		35	25
60	250	SR4				35	25

Table 4. Limiting Data for Example 2[a]

Sinks SK*j*	flow rate, F_j (t/h)	concentration, C_j (ppm)	Sources SR*i*	flow rate, F_i (t/h)	concentration, C_i (ppm)
SK1	36.364	25	SR1	36.364	80
SK2	44.308	25	SR2	44.308	90
SK3	22.857	25	SR3	22.857	200
SK4	60.000	50	SR4	60.000	100
SK5	40.000	50	SR5	40.000	800
SK6	12.500	400	SR6	12.500	800
SK7	5.000	200	SR7	5.000	600
SK8	10.000	0	SR8	10.000	100
SK9	80.000	50	SR9	80.000	300
SK10	43.333	150	SR10	43.333	300
$\Sigma_j F_j$	**354.3618**		**$\Sigma_i F_i$**	**354.3618**	

[a] Data taken from refs 8 and 9.

Table 5. Network Design for Example 2 Represented as Matching Matrices

		F_j (t/h)	10	36.364	44.308	22.857	60	40	80	43.333	5	12.5	166.266
		C_j (ppm)	0	25	25	25	50	50	50	150	200	400	
F_i (t/h)	C_i (ppm)	SR*i* \ SK*j*	SK8	SK1	SK2	SK3	SK4	SK5	SK9	SK10	SK7	SK6	WW
166.266	0	FW	10	25	30.462	15.714	27.435	17.332	40	0.323 ←	0.323		
36.364	80	SR1		11.364	13.846	7.143		4.011					
44.308	90	SR2					25.651	18.657		1.42			
60	100	SR4					6.914		40	11.666 ←	1.42		
10	100	SR8								10	3.81		
22.857	200	SR3								21.667 →	1.19		
80	300	SR9								←	2.067	12.5	65.433
43.333	300	SR10								2.067			43.333
5	600	SR7											5
40	800	SR5											40
12.5	800	SR6											12.5

interconnections in a water network at the cost of a freshwater penalty. Conceptually, WPA is equivalent to the utility path in removing the smallest heat exchanger unit in a heat exchanger network,[21] or a mass-load path to reduce the number of mass exchangers in a mass exchange network.[22] A water path is a continuous route that starts from a freshwater source, linked with the sink−source connections, and ends at a wastewater sink. By shifting the amount of water flow rate along a water path from a "cleaner" sink−source match (of lower concentration) to another "dirtier" sink−source match (higher concentration), an equal amount of freshwater can be added as a penalty to replace the shifted water load. This also corresponds to an increase in the wastewater flow rates. Most often, a water path is a connection with many bend (or a *kink*). To minimize the water penalty, we propose to remove the smallest match among all L-kink connections within all available water paths. If it is

Table 6. Matching Matrices for Example 2 after Source Shift

		F_j (t/h)	10	36.364	44.308	22.857	60	40	80	43.333	5	12.5	166.266
		C_j (ppm)	0	25	25	25	50	50	50	150	200	400	
F_i (t/h)	C_i (ppm)	SK*j* / SR*i*	SK8	SK1	SK2	SK3	SK4	SK5	SK9	SK10	SK7	SK6	WW
166.266	0	FW	10	25	30.462	15.714	27.435	17.332	40	0.323			
36.364	80	SR1		11.364	13.846	7.143		4.011					
44.308	90	SR2					25.651	18.657					
60	100	SR4					6.914		40	13.086			
10	100	SR8								10			
22.857	200	SR3								17.856	5		
80	300	SR9								2.067		12.5	65.433
43.333	300	SR10											43.333
5	600	SR7											5
40	800	SR5											40
12.5	800	SR6											12.5

Table 7. Network Design for Example 1 after Two-Point Shifts between SK4 and the Wastewater Stream

		F_j (t/h)	50	100	80	70	50
		C_j (ppm)	20	50	100	200	
F_i (t/h)	C_i (ppm)	SK*j* / SR*i*	SK1	SK2	SK3	SK4	WW
70	0	FW	30	40			
50	50	SR1	20	30			
100	100	SR2		20	80		
70	150	SR3		10		60	
60	250	SR4				10	50

justified that a simpler water network is needed, more L-kink connections may be removed and, hence, a larger water penalty is experienced.

Similar to SSA, WPA can be a useful tool in developing different network alternatives, with the different price of a water penalty. The application of WPA will be illustrated using two examples.

Example 1 (Continued). From the previous section, the preliminary water network of Example 1, which is generated by NNA and later evolved by improved SSA, is shown in Table 3. This water network was further simplified by a two-point shift algorithm[15] (which involved matches between SK4−SR3 and WW−SR3, as well as SK4−SR4 and WW−SR4), resulting in a new network which is shown in Table 7.[15] Prakash and Shenoy[15] also showed that the complexity of this network can be further reduced by incurring a freshwater penalty, using the two-point shift algorithm.[15] However, the two-point shift procedure is tedious and cumbersome. Hence, we propose to improve the network evolution step by using a WPA technique.

As shown in Table 8, two water paths are identified in this network, where a portion of these paths are overlapping. Path 1 that is shown using solid line connects matches of SK2−FW, SK2−SR3, SK4−SR3, SK4−SR4, and WW−SR4. Path 2, which is shown as a dashed line in the table, connects between SK1−FW, SK1−SR1, SK2−SR1, SK2−SR3, SK4−SR3, SK4−SR4, and WW−SR4. Note that Path 1 consists of two L-kinks, which are SK2−SR3 and SK4−SR4. Both matches possess the same water flow rate of 10 t/h. Meanwhile, Path 2 contains one extra L-kink, as compared to Path 1 (i.e., SK1−SR1, with a flow rate of 20 t/h). The interconnections between SK2−SR3 and SK4−SR4 are chosen to be eliminated to evolve the network, because these interconnections contain the smallest flow rate among all L-kink connections. Hence, a freshwater flow of 10 t/h is added into process SK2 (in the row of FW). Next, a water flow of 10 t/h, which was originally fed from SR3 to this sink, is shifted along Path 1 to a "dirtier" sink (i.e., SK4). Water sink SK4 is now fully satisfied by SR3. Hence, the SK4−SR4 match is removed and a water flow of 10 t/h from SR4 is sent to the wastewater for discharge. The evolved network is shown in Table 9. Note that the resulting network is essentially the same as that reported by Prakash and Shenoy.[15] However, the WPA technique is simpler, in comparison to the two-point shift algorithm, which is iterative in nature.[15] As shown, with a freshwater penalty of 10 t/h, two interconnections (i.e., SK2−SR3 and SK4−SR4) are eliminated from the original design (see Table 8).

On the other hand, one may choose to evolve the network using Path 2. By adding a freshwater flow of 10 t/h to sink

Table 8. Network Evolution with Water Path (Example 1)

		F_j (t/h)	50	100	80	70	50
		C_j (ppm)	20	50	100	200	
F_i (t/h)	**C_i (ppm)**	**SKj** / **SRi**	SK1	SK2	SK3	SK4	WW
70	0	FW	30	40			
50	50	SR1	20	30			
100	100	SR2		20	80		
70	150	SR3		10	10	60	
60	250	SR4				10	10 50

Table 9. Network Design for Example 1 after Water Path Analysis (Freshwater Penalty of 10 t/h)

		F_j (t/h)	50	100	80	70	60
		C_j (ppm)	20	50	100	200	
F_i (t/h)	**C_i (ppm)**	**SKj** / **SRi**	SK1	SK2	SK3	SK4	WW
80	0	FW	30	50			
50	50	SR1	20	30			
100	100	SR2		20	80		
70	150	SR3				70	
60	250	SR4					60

SK1, a flow of 10 t/h of the process water in the SK1−SR1 match is shifted to the SK2−SR1 match. The remainder of the water load shifting remains the same as that in Path 1. Based on this example, two interconnections have been eliminated from the original water network by adding a freshwater flow of 10 t/h. Note also that the same network can also be evolved from Table 3 using WPA and followed by a two-point shift algorithm (which involves matches between SK4−SR3 and WW−SR3, as well as SK4−SR4 and WW−SR4). Hence, the sequence between WPA and the two-point shift algorithm does not affect the final network design.

To further evolve the water network, a greater water penalty is expected. However, the evolved network serves as an alternative for the process designer in regard to synthesizing a water network. Two alternative networks with an additional freshwater penalty of 20 t/h are shown in Tables 10 and 11. In Table 10, a freshwater flow of 20 t/h that is added to SK1 results in the removal of the SK2−SR1 match. However, in this alternative, the total number of interconnection remains the same, in comparison to the network in Table 9 (eight matches). This is due to the new match (i.e., WW−SR1) that emerges upon the removal of the SK2−SR1 match (water paths SK1−FW, SK1−SR1, and WW−SR1). In Table 11, water path SK1−FW, SK1−SR1, SK2−SR1, SK2−SR2, and WW−SR2 is utilized, which leads to the removal of two recycle matches (SK1−SR1 and SK2−SR2) and the emergence of a wastewater match (WW−SR2). Hence, the ultimate result is a network with seven matches (see Table 11).

Example 3. To illustrate the wide application of the WPA technique, another example from Sorin and Bédard,[4] with six water sinks and five sources, is used. The limiting water data for this example are given in Table 12. The minimum water flow rates are targeted as 200 t/h for freshwater and 120 t/h for wastewater, with two pinch concentrations identified at 100 and 180 ppm.[11−13,20]

One possible water network for this example, which designed using NNA, is shown in the matching matrix in Table 13. Four water paths are identified from the matching matrix (see Table 13). As shown, Path 1 (solid line) connects matches between SK3−FW, SK3−SR1, SK4−SR1, SK4−SR4, SK6−SR4, SK6−SR6, and WW−SR6; although Path 2 (dashed line) connects matches between SK2−FW, SK2−SR1, SK5−SR1, SK5−SR4, SK6−SR4, SK6−SR6, and WW−SR6, Path 3 initiates from the SK2−FW match and passes by SK2−SR1, SR4−SR1, and

Table 10. Alternative Network for Example 1 with a Freshwater Penalty of 30 t/h (Eight Matches)

		F_j (t/h)	50	100	80	70	80
		C_j (ppm)	20	50	100	200	
F_i (t/h)	**C_i (ppm)**	**SR*i* \ SK*j***	SK1	SK2	SK3	SK4	WW
100	0	FW	50	50			
50	50	SR1		30			20
100	100	SR2		20	80		
70	150	SR3				70	
60	250	SR4					60

Table 11. Alternative Network for Example 1 with a Freshwater Penalty of 30 t/h (Seven Matches)

		F_j (t/h)	50	100	80	70	80
		C_j (ppm)	20	50	100	200	
F_i (t/h)	**C_i (ppm)**	**SR*i* \ SK*j***	SK1	SK2	SK3	SK4	WW
100	0	FW	50	50			
50	50	SR1		50			
100	100	SR2			80		20
70	150	SR3				70	
60	250	SR4					60

Table 12. Limiting Data for Example 3[a]

Sinks			Sources		
SK*j*	flow rate, F_j (t/h)	concentration, C_j (ppm)	SR*i*	flow rate, F_i (t/h)	concentration, C_i (ppm)
SK1	120	0	SR1	120	100
SK2	80	50	SR2	80	140
SK3	80	50	SR3		
SK4	140	140	SR4	140	180
SK5	80	170	SR5	80	230
SK6	195	240	SR6	195	250
ΣF_j	**695**		**ΣF_i**	**615**	

[a] Data taken from ref 4.

the remainder of Path 1 (from SR4−SR1 onward). Path 4 initiates from the SK3−FW match, passes SK3−SR1 and SK5−SR1, and continues with the remainder of Path 2 (from SR5−SR1 onward). Hence, the richness of design provides more flexibility to the process designer in evolving a water network. As the heuristics suggest, the sink−source match with the smallest flow rate that is located at the L-kink within all water paths is chosen to be eliminated. It is observed that all paths have three L-kinks; i.e., Path 1 has SK3−SR1, SK4−SR4, and SK6−SR6; Path 2 has SK2−SR1, SK5−SR4, and SK6−SR6; Path 3 has SK2−SR1, SK4−SR4, and SK6−SR6; and Path 4 has SK3−SR1, SK5−SR4, and SK6−SR6. Among all the L-kinks, the SK4−SR4 match in Paths 1 and 3 has the smallest flow rate of 30 t/h and, hence, is selected to be removed. Therefore, a freshwater flow of 30 t/h is added to the water path. Note that the freshwater may be added either to process SK3 (Path 1) or SK2 (Path 3), because the majority sections of these paths are the same. This provides more flexibility for the designer to evolve a network based on other constraints. In this example, a freshwater flow of 30 t/h is added to sink SK3; hence, a process water flow of 30 t/h from the SK3−SR1 match is shifted to the SK4−SR1 match. This leads to a process water shift of 30 t/h from the SK4−SR4 match to SK6−SR4 and finally, a water flow of 30 t/h is shifted from SK6−SR6 to WW−SR6 (i.e., wastewater discharge). As a result, the SK4−SR4 match is eliminated, with a freshwater penalty of 30 t/h. The resulting network after the water shift is shown in Table 14.

Table 15 shows that the opportunity to evolve the water network has not been exhausted, because the existence of Path 2 (or Path 4) presents another degree of freedom for the designer to further evolve the water network. With this degree of freedom, alternative networks can be evolved. Following the same WPA procedure, a freshwater flow of 10 t/h (which is identified from the smallest L-kink connection of the SK3−SR1 match) is added to sink SK3, with a water shift of 10 t/h from the SK3−SR1 match to the SK5−SR1 match. Thus, the excess reuse water flow of 10 t/h is shifted to the wastewater stream via the WW−SR6 match. Table 16 shows the network with a total freshwater penalty of 40 t/h. In this case, two interconnections, SK4−SR4 and SK3−SR1, have been eliminated.

Similar to the previously discussed Example 1, a greater water penalty would be expected if one were to further evolve the network. In Table 16, the next-smallest (L-kink connection)

Table 13. Network Evolution with Water Path Analysis (Example 3)

		F_j (t/h)	120	80	80	140	80	195	120
		C_j (ppm)	0	50	50	140	170	240	
F_i (t/h)	C_i (ppm)	SR*i* \\ SK*j*	SK1	SK2	SK3	SK4	SK5	SK6	WW
200	0	FW	120	40	40				
120	100	SR1		40	40	30	10		
80	140	SR2				80			
140	180	SR4				30	70	40	
80	230	SR5						80	
195	250	SR6						75	120

Table 14. Network Design with a Freshwater Penalty of 30 t/h

		F_j (t/h)	120	80	80	140	80	195	150
		C_j (ppm)	0	50	50	140	170	240	
F_i (t/h)	C_i (ppm)	SR*i* \\ SK*j*	SK1	SK2	SK3	SK4	SK5	SK6	WW
230	0	FW	120	40	70				
120	100	SR1		40	10	60	10		
80	140	SR2				80			
140	180	SR4					70	70	
80	230	SR5						80	
195	250	SR6						45	150

water penalty would be 35 t/h (i.e., the SK6−SR6 match). To eliminate this match, one may utilize any path that connects this match, e.g., paths SK6−FW, SK6−SR6, and WW−SR6 (with the same number of interconnections, because of the emergence of a new match, i.e., SK6−FW) or paths SK2−FW, SK2−SR1, SK5−SR1, SK5−SR4, SK6−SR4, SK6−SR6, and WW−SR6 (with one match removed). However, note that eliminating this match means that one experiences a total water penalty of 75 t/h. If this penalty is deemed unworthy, the SK6−SR6 match shall remain.

Conclusion

The source shift algorithm (SSA) has recently been developed to reduce the interconnections in a preliminary water network. With the new guidelines proposed in this work, tedious and time-consuming steps of the algorithm have been removed. Stream interconnection can be readily reduced from the preliminary water network without iterative steps while the minimum water flow rates are observed.

In addition, a new concept, which is known as water path analysis (WPA), is proposed in this work. WPA is used to reduce number of interconnections among the network and evolve the network by incurring penalties of freshwater and wastewater flow. In practice, both concepts are useful, because they offer numerous alternative network designs, which may be subjected to other constraints, such as geographical, operational, and maintenance constraints.

Table 15. Water Path with a Freshwater Penalty of 10 t/h

		F_j (t/h)	120	80	80	140	80	195	150
		C_j (ppm)	0	50	50	140	170	240	
F_i (t/h)	C_i (ppm)	SRi \ SKj	SK1	SK2	SK3	SK4	SK5	SK6	WW
230	0	FW	120	40	70				
120	100	SR1		40	10	60	10		
80	140	SR2				80			
140	180	SR4					70	70	
80	230	SR5						80	
195	250	SR6						45	150

Table 16. Final Network Design with a Freshwater Penalty of 40 t/h

		F_j (t/h)	120	80	80	140	80	195	160
		C_j (ppm)	0	50	50	140	170	240	
F_i (t/h)	C_i (ppm)	SRi \ SKj	SK1	SK2	SK3	SK4	SK5	SK6	WW
240	0	FW	120	40	80				
120	100	SR1		40		60	20		
80	140	SR2				80			
140	180	SR4					60	80	
80	230	SR5						80	
195	250	SR6						35	160

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