

Simultaneously Designing and Targeting for Networks with Multiple Resources of Different Qualities^{*}

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Abstract This paper presents a new design procedure for the networks with multiple resources, such as hydrogen and water, of different qualities. The minimum consumption targets of the resources and pinch-causing sources can be identified as well during design. The objective of this work is to reduce the consumption of the resources with higher quality due to their higher cost. A few examples are investigated to show the proposed method. For a network of single resource with single contaminant, there is often only one pinch point for the resource. On the other hand, for a network of multiple resources with single contaminant, there might be a few different pinch points. Each resource might have its own pinch point, if its amount is sufficient. The contaminant concentration of the pinch-causing source for a resource with lower concentration will be below that of the higher-concentration resource(s).

Keywords fresh resource target, multiple resources, multiple pinch points, pinch analysis

1 INTRODUCTION

The reduction of fresh resource consumption and waste discharge in chemical industry is imperative under the situation of the stricter environmental protection and the rising cost of waste treatment. Since Wang and Smith [1] presented water-pinch-analysis, many approaches have been proposed to design or find the minimum freshwater consumption targets for the networks with single freshwater resource [2–11]. Alves and Towler [12] addressed the minimum consumption target for hydrogen networks. Agrawal and Shenoy [10] proposed an approach to target and design water and hydrogen networks.

In the literature, most researches focus on single fresh resource systems. Wang and Smith [9] discussed the networks with multiple fresh resources briefly. However, no detailed research was carried out. For the single fresh resource networks, most of researchers considered the resource as 100% pure, such as 100% purity freshwater. In fact, the fresh resource is often not 100% pure in industrial practice. Most importantly, there are often several fresh resources with different qualities available. Generally speaking, the higher the quality of the fresh resource, the more expensive it is. Therefore, the use of the higher quality resource should be minimized at the expensing of lower quality ones. This means that, in the targeting and design of the resource-using network with multiple fresh resources of different qualities, the quality of the resources should be considered as well.

Recently, a few researchers addressed impure fresh resource or multi-resource problems. Shenoy and Bandyopadhyay [13] developed a methodology to

target multiple resources through the source composite curves in order to minimize the operating cost of the overall process. The methodology was presented in both graphical and algorithmic forms. A few examples were investigated to demonstrate that the method can be applied to the problems of material management through appropriate reuse and recycle. Alwi and Manan [14] developed a graphical method, based on some heuristic rules, to determine the minimum flow rate targets for a single resource (or utility) and multiple resources using source and sink (demand) water composite curves. Foo [15] addressed the problems for single and multiple feeds of impure fresh water by using the numerical targeting tool of water cascade analysis technique [4]. A three-step procedure was proposed based on the modified water cascade analysis technique, which leads to the minimum pure and impure fresh water resources. Other researches on multi-resource targeting include the water source diagram proposed by Gomes *et al.* [16] and an algebraic approach proposed by Almutlaq and El-Halwagi [17].

The research mentioned above mainly addressed the resource-using networks of single contaminant. For the water-using networks of multiple contaminants, many approaches have also been proposed [18–28].

This paper presents a new method to design and target the networks with multiple resources of different qualities. The procedure proposed is simple to use compared to the literature methods.

2 THEORY OF THE NEW METHOD

In a resource-using network, there is a set of

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resource-related units. The inlet stream of each unit is called demand because it will need fresh resource or reuse the outlet streams of other units. The outlet stream of each unit is called internal source, because it can be reused for the other units. Some outlet (or source) streams cannot be reused by the demands because their qualities are too low and will be discharged as waste. Therefore, the waste belongs to sources instead of demands, as pointed out by Liu *et al.* [8]. There are also a few external sources with different qualities which can be used as source streams with or without flow rate limitations. In order to distinguish the external sources from the internal ones, the external sources are defined as Resources. The objective is to design the networks with the minimum consumption of the resources by considering both the amounts and the qualities of the resources.

Generally speaking, external sources are more expensive than internal sources, if they have the same quality, because of the following reasons: internal sources are “generated” in the network, because they are the outlet streams of the resource-using-units, and external sources are often purchased; external sources need shipment cost and storage cost. For a single contaminant system, concentration of the contaminant is often the most important factor of stream quality. For example, in a water-using network, the lower the concentration of the contaminant, the higher the quality of the water stream, and the more expensive of the stream.

The above statement is true for the same kind of sources (internal or external). However, for a network with multiple external sources, it is necessary to consider costs of different kind of sources. For a network with multiple external sources, internal source S_i^{In} is assumed to be cheaper than external source S_{k+1}^{Ex} , if $C_k^{\text{Ex}} < C_i^{\text{In}} < C_{k+1}^{\text{Ex}}$, where C_{k+1}^{Ex} is the concentration of S_{k+1}^{Ex} , and C_i^{In} is the concentration of S_i^{In} . In this situation, internal source S_i^{In} will be used before external source S_{k+1}^{Ex} in order to reduce consumption of the resources.

Compared to the networks with single resource, a network with multiple resources often has special features. For a network with single resource, there is often only one pinch point. However, for a network with multiple resources, there might be a few different pinch points. Each resource might have its own pinch point, if its amount is sufficient. The concentration of the pinch-causing source of a resource will be below that of the higher-concentration resource (s). This is similar to the situation as discussed by Feng *et al.* [29] for regeneration target problems.

In the targeting and design procedure, it should be emphasized that the higher quality resource should be saved as much as possible. Therefore, a demand can be satisfied by the sources in analogy with the nearest neighbors approach proposed by Prakash and Shenoy [6], who have proved that the nearest neighbors approach can provide optimal solution for the water-using networks of single contaminant. In nearest neighbors approach, a demand with concentration C_d

will be satisfied by a source whose concentration is just higher than C_d and a source whose concentration is just lower than C_d . For convenience, the source whose concentration is just higher than C_d is named as the higher concentration source (HCS) and the source whose concentration is just lower than C_d as the lower concentration source (LCS). If the concentration of the resource and that of the internal source are the same, the internal source will be reused first as discussed earlier. In fact, a demand stream might need a few source streams and a source stream might be reused by a few demand streams. However, in order to simplify the design procedure, only satisfying a demand stream by its HCS and LCS in each operation is considered. When satisfying a demand with its HCS and LCS, often only one of the streams is the determining-stream, which will determine the amount of the other two streams.

Now, the determination of the determining-stream and the calculation of the amounts of the other two streams are considered based on the amount of the determining-stream. The concentrations of the demand, its HCS and LCS are presented by C_d , C_{sh} , and C_{sl} , respectively. The mass load, flow rate and concentration of a stream have the following relationship:

$$m = F \times C \quad (1)$$

If a demand stream with amount of F_d can be satisfied by its HCS with amount of F_{sh} and its LCS with amount of F_{sl} , their relationship can be expressed as follows:

$$F_d = F_{\text{sh}} + F_{\text{sl}} \quad (2)$$

$$F_d \times C_d = F_{\text{sh}} \times C_{\text{sh}} + F_{\text{sl}} \times C_{\text{sl}} \quad (3)$$

The amounts of the streams F_d , F_{sh} and F_{sl} are named as Matched-stream Amounts, and the streams as Matched-streams, if they meet the conditions of both Eqs. (2) and (3). By solving F_{sl} and F_{sh} from Eq. (2) and substituting them to Eq. (3), the following calculations can be obtained:

$$F_d \times C_d = F_{\text{sh}} \times C_{\text{sh}} + (F_d - F_{\text{sh}}) \times C_{\text{sl}} \quad (4)$$

$$F_d = F_{\text{sh}} \times (C_{\text{sh}} - C_{\text{sl}}) / (C_d - C_{\text{sl}}) \quad (5)$$

$$F_{\text{sh}} = F_d \times (C_d - C_{\text{sl}}) / (C_{\text{sh}} - C_{\text{sl}}) \quad (6)$$

$$F_d = F_{\text{sl}} \times (C_{\text{sh}} - C_{\text{sl}}) / (C_{\text{sh}} - C_d) \quad (7)$$

The following ratios can be written from Eqs. (5)–(7):

$$F_d : F_{\text{sh}} : F_{\text{sl}} = (C_{\text{sh}} - C_{\text{sl}}) : (C_d - C_{\text{sl}}) : (C_{\text{sh}} - C_d) \quad (8)$$

$$\text{or } \frac{F_d}{C_{\text{sh}} - C_{\text{sl}}} = \frac{F_{\text{sh}}}{C_d - C_{\text{sl}}} = \frac{F_{\text{sl}}}{C_{\text{sh}} - C_d} \quad (9)$$

Equations (8) and (9) show the relationships between the matched-streams. For the factual flow rates of a demand $F_{d,i}^{\text{R}}$, its HCS $F_{\text{sh},i}^{\text{R}}$, and LCS $F_{\text{sl},i}^{\text{R}}$, they might not meet Eqs. (8) and (9). Obviously, the stream corresponding to the determining-stream-ratio (DSR) defined in Eq. (10) will determine the matched amounts of the other streams. The stream corresponding to DSR is defined as the Determining-stream, and the other two streams as the Non-determining-streams.

$$\text{DSR} = \min \left[\frac{F_{d,i}^R}{C_{sl} - C_{sl}}, \frac{F_{sh,i}^R}{C_d - C_{sl}}, \frac{F_{sl}^R}{C_{sh} - C_d} \right] \quad (10)$$

When the determining-stream is found, the amounts of the non-determining-streams can be calculated by using the following equations:

$$\left. \begin{aligned} F_d &= \text{DSR} \times (C_{sh} - C_{sl}) \\ F_{sl} &= \text{DSR} \times (C_{sh} - C_d) \\ F_{sh} &= \text{DSR} \times (C_d - C_{sl}) \end{aligned} \right\} \quad (11)$$

When a demand stream with amount of F_d is satisfied by its LCS and HCS with matched amounts F_{sl} and F_{sh} , respectively, the determining-stream is used up. The remainder amounts of the non-determining-streams will be the factual amounts for next step. For a resource with unlimited amount, it will not be a determining-stream.

The design and targeting procedure is as follows:

(1) Arrange the demand and source streams in ascending order of the concentration, respectively;

(2) For each demand stream, find its HCS and LCS. Identify the determining-stream according to Eq. (10), and calculate the matched amounts of the non-determining-streams by using Eq. (11);

(3) Subtracting the matched amount from the factual amount for each stream and the result is the factual amount of the stream for the next step. Go back to Step (2);

The maximum cumulative amount of each fresh resource will be its target; and the source corresponding to the target will be the pinch-causing source. The detailed calculation for Step (3) will be illustrated in the examples.

3 CASE STUDIES

3.1 Example 1

The example is a hydrogen network and taken from Alves and Towler [12]. In this example, the fresh resource has a 5% (by mol) impurity. Table 1 lists the original data for this example. Table 2 lists the generated data for this example. In Table 2, the streams with the same concentration in Table 1 have been lumped as one stream. In Table 2, the demand and source streams are arranged in ascending order of their concentrations, respectively.

Table 1 Original data for Example 1

Demand		Source	
$C_d/\%$ (by mol)	$F_d^R/\text{mol}\cdot\text{s}^{-1}$	$C_s/\%$ (by mol)	$F_s^R/\text{mol}\cdot\text{s}^{-1}$
19.39	2495	7	623.8
21.15	180.2	20	415.8
22.43	554.4	25	1801.9
24.86	720.7	25	138.6
		27	346.5
		30	457.4

Table 2 Generated data for Example 1

Demand		Source	
$C_d/\%$ (by mol)	$F_d^R/\text{mol}\cdot\text{s}^{-1}$	$C_s/\%$ (by mol)	$F_s^R/\text{mol}\cdot\text{s}^{-1}$
19.39	2495	5	
21.15	180.2	7	623.8
22.43	554.4	20	415.8
24.86	720.7	25	1940.5
		27	346.5
		30	457.4

For the first demand of 19.39%, its HCS and LCS are the sources of 20% and 7%, respectively. Here, the source of 7% is the internal source whose concentration is just lower than 19.39%. DSR can be calculated from Eq. (10):

$$\begin{aligned} \text{DSR} &= \min \left[\frac{F_{d,i}^R}{C_{sh} - C_{sl}}, \frac{F_{sh,i}^R}{C_d - C_{sl}}, \frac{F_{sl}^R}{C_{sh} - C_d} \right] \\ &= \min \left[\frac{2495}{20 - 7}, \frac{415.8}{19.39 - 7}, \frac{623.8}{20 - 19.39} \right] \\ &= \min[191.92, 33.56, 1022.62] \\ &= 33.56 \end{aligned}$$

Thus the HCS, the source of 20%, which corresponds to the DSR, is the determining-stream. F_d and F_{sl} can be obtained from Eq. (11):

$$F_d = \text{DSR} \times (C_{sh} - C_{sl}) = 33.56 \times (20 - 7) = 436.27$$

$$F_{sl} = \text{DSR} \times (C_{sh} - C_d) = 33.56 \times (20 - 19.39) = 20.47$$

The results for Step (1) are listed in row 1 of Table 3. The determining-stream, the HCS in Step (1), is used up. Then the source stream of 25% will be the HCS for Step (2). For a non-determining-stream, its remainder amount in a step will be its factual amount for the next step. For example, the demand stream of 19.39% is a non-determining-stream. The remainder amount of the demand in Step (1) will be:

$$F_{d,1}^R - F_{d,1} = 2495 - 436.27 = 2058.73 \text{ mol}\cdot\text{s}^{-1}$$

The amount of $2058.73 \text{ mol}\cdot\text{s}^{-1}$ will be the factual amount of the demand in Step (2). Similarly, the factual amount of the LCS can be obtained.

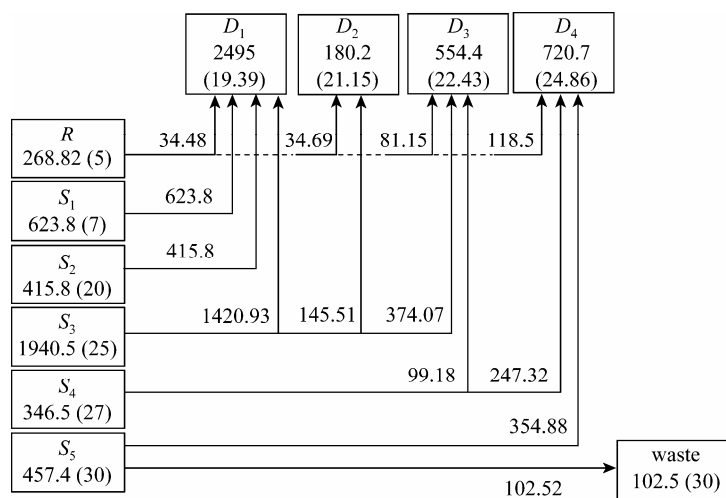
All the factual amounts of the demand, the HCS and the LCS are listed in row 2 for Step (2). Then the calculation for Step (2) can be started. For Step (2), the demand is 19.39%, and the HCS and LCS are the sources of 25% and 7%, respectively. The determining-stream for Step (2) corresponds to:

$$\begin{aligned} \text{DSR} &= \min \left[\frac{2058.73}{25 - 7}, \frac{1940.5}{19.39 - 7}, \frac{603.33}{25 - 19.39} \right] \\ &= \min[114.37, 156.62, 107.55] \\ &= 107.55 \end{aligned}$$

Then, the LCS, which corresponds to the DSR, is

Table 3 The matched data of the demand, HCS and LCS streams for Example 1

$C_d/\%$ (by mol)	$F_d/\text{mol}\cdot\text{s}^{-1}$	$F_d^R/\text{mol}\cdot\text{s}^{-1}$	$C_{sh}/\%$ (by mol)	$F_{sh}/\text{mol}\cdot\text{s}^{-1}$	$F_{sh}^R/\text{mol}\cdot\text{s}^{-1}$	$C_{sl}/\%$ (by mol)	$F_{sl}/\text{mol}\cdot\text{s}^{-1}$	$F_{sl}^R/\text{mol}\cdot\text{s}^{-1}$
19.39	436.27	2495.00	20	415.80	415.80	7	20.47	623.80
19.39	1935.81	2058.73	25	1332.49	1940.50	7	603.33	603.33
19.39	122.91	122.91	25	88.44	608.01	5	34.48	
21.15	180.2	180.2	25	145.51	519.58	5	34.69	
22.43	429.22	554.40	25	374.07	374.07	5	55.15	
22.43	125.18	125.18	27	99.18	346.50	5	26.00	
24.86	273.97	720.70	27	247.32	247.32	5	26.65	
24.86	446.73	446.73	30	354.88	457.40	5	91.85	

**Figure 1** The structural design for Example 1 (The values show flow rate in $\text{mol}\cdot\text{s}^{-1}$ with contaminant mol percentage concentrations within braces)

the determining-stream. Similar procedure can be carried out to calculate the amounts of the non-determining-streams and the amounts of the next step. The results are listed in row 2 of Table 3.

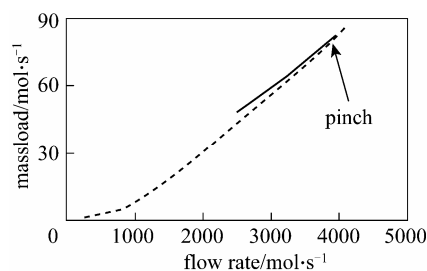
Now the LCS of 7% is used up. The LCS for Step (3) will be the 5% impure fresh resource, whose amount is much enough for the process. Therefore, the LCS will not be the determining-stream. The determining-stream will be either the demand stream or the HCS. The calculation procedure is the same as above. Table 3 lists the matched data and factual data of the demand, the HCS and LCS streams for this example. The determining-stream for each step is printed in bold in Table 3.

From the data in Table 3, it is found that the target (or the maximum cumulative amount) of the fresh resource of 5% will be:

$$34.48 + 34.69 + 55.15 + 26.00 + 26.65 + 91.85 = 268.8 \text{ mol}\cdot\text{s}^{-1}$$

where the flow rates of the fresh resource streams included in the calculation are shadowed in Table 3. The result obtained is the same as that obtained by El-Halwagi *et al.* [3], Alves and Towler [12] and Shenoy and Bandyopadhyay [13]. A design obtained is

shown in Fig. 1. Fig. 2 shows the shifted composite curves for this example. The detailed discussion about the composite curves can be found in the work of El-Halwagi *et al.* [3].

**Figure 2** The shifted composite curves for Example 1
— demand; ---- source

3.2 Example 2

The data of Example 2 are shown in Table 4. There are two fresh resources with infinite amounts: a source of impure resource stream with concentration of $40 \text{ mg}\cdot\text{L}^{-1}$ and a hundred-percent fresh resource stream.

From Table 4, it can be seen that the first demand

Table 4 Original data for Example 2

Demand		Source	
$C_d/\text{mg}\cdot\text{L}^{-1}$	$F_d^R/\text{t}\cdot\text{h}^{-1}$	$C_s/\text{mg}\cdot\text{L}^{-1}$	$F_s^R/\text{t}\cdot\text{h}^{-1}$
0	120	0	
50	160	40	
100	140	30	60
200	80	150	120
300	100	250	150
		400	140

stream only needs the pure resource. For the demand stream of $50\text{ mg}\cdot\text{L}^{-1}$, its HCS and LCS are the sources of $150\text{ mg}\cdot\text{L}^{-1}$ and $30\text{ mg}\cdot\text{L}^{-1}$, respectively. Here the internal source of $30\text{ mg}\cdot\text{L}^{-1}$ is used before the external source of $40\text{ mg}\cdot\text{L}^{-1}$, because the internal one is cheaper than the external one as discussed earlier. DSR can be calculated from Eq. (10):

$$\begin{aligned}\text{DSR} &= \min\left[\frac{160}{150-30}, \frac{120}{50-30}, \frac{60}{150-50}\right] \\ &= \min[1.33, 6, 0.6] \\ &= 0.6\end{aligned}$$

The LCS, the source of $30\text{ mg}\cdot\text{L}^{-1}$ corresponding to the DSR, is the determining-stream. The DSR value

can be used to calculate the matched amounts of the other two streams:

$$F_{d,2} = \text{DSR} \times (C_{\text{sh}} - C_{\text{sl}}) = 0.6 \times (150 - 30) = 72\text{ t}\cdot\text{h}^{-1}$$

$$F_{\text{sh},2} = \text{DSR} \times (C_d - C_{\text{sl}}) = 0.6 \times (50 - 30) = 12\text{ t}\cdot\text{h}^{-1}$$

The LCS is used up, now. Then the LCS for the next step is the infinite source of $40\text{ mg}\cdot\text{L}^{-1}$. As discussed above, the infinite source will not be the determining-stream. The remainders of the non-determining-streams are:

$$F_{d,3}^R = F_{d,2}^R - F_{d,2} = 160 - 72 = 88\text{ t}\cdot\text{h}^{-1}$$

$$F_{\text{sh},3}^R = F_{\text{sh},2}^R - F_{\text{sh},2} = 120 - 12 = 108\text{ t}\cdot\text{h}^{-1}$$

Similar procedures can be carried out for the following steps.

Table 5 lists the matched data and factual data of the demand, the HCS and LCS streams. The flow rate of the determining-stream for each step is printed in bold in Table 5. The design of the network is shown in Fig. 3 and the shifted composite curves for this example are shown in Fig. 4. From Fig. 4, it is found that there are two pinch points for this example. The pinch-causing sources are the source of $0\text{ mg}\cdot\text{L}^{-1}$ for the resource of $0\text{ mg}\cdot\text{L}^{-1}$, and the source of $250\text{ mg}\cdot\text{L}^{-1}$ for the resource of $40\text{ mg}\cdot\text{L}^{-1}$, respectively. From this example, it can be seen that if the amounts of the resources are sufficient, each resource might have its pinch point. The concentration of the pinch-causing

Table 5 The matched data of the demand, HCS and LCS streams for Example 2

$C_d/\text{mg}\cdot\text{L}^{-1}$	$F_d/\text{t}\cdot\text{h}^{-1}$	$F_d^R/\text{t}\cdot\text{h}^{-1}$	$C_{\text{sh}}/\text{mg}\cdot\text{L}^{-1}$	$F_{\text{sh}}/\text{t}\cdot\text{h}^{-1}$	$F_{\text{sh}}^R/\text{t}\cdot\text{h}^{-1}$	$C_{\text{sl}}/\text{mg}\cdot\text{L}^{-1}$	$F_{\text{sl}}/\text{t}\cdot\text{h}^{-1}$	$F_{\text{sl}}^R/\text{t}\cdot\text{h}^{-1}$
0	120	0				0	120	
50	72	160	150	12	120	30	60	60
50	88	88	150	8	108	40	80	
100	140	140	150	76.36	100	40	63.64	
200	47.27	80	250	23.63	150	150	23.64	23.64
200	32.73	32.73	250	24.94	126.37	40	7.79	
300	100	100	400	33.33	140	250	66.67	101.43

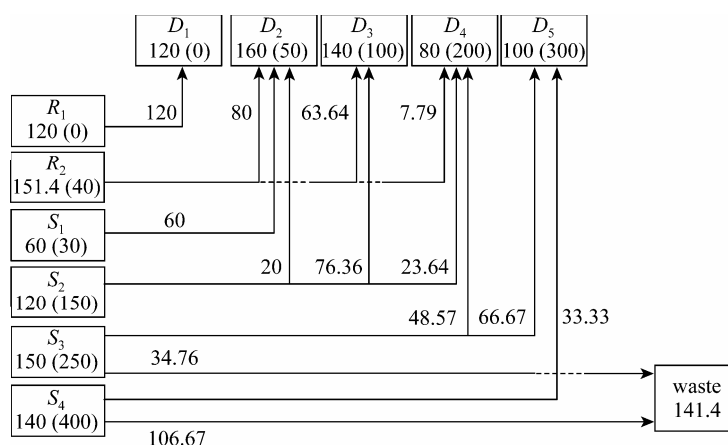


Figure 3 The structural design for Example 2 (The values show flow rate in $\text{t}\cdot\text{h}^{-1}$ with contaminant concentrations in $\text{mg}\cdot\text{L}^{-1}$ within braces)

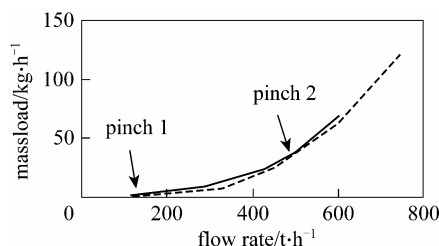


Figure 4 The shifted composite curves for Example 3
— demand; ---- source

source of $0 \text{ mg}\cdot\text{L}^{-1}$ resource, which is $0 \text{ mg}\cdot\text{L}^{-1}$, is below the concentration of the resource of $40 \text{ mg}\cdot\text{L}^{-1}$.

The pure resource target is $120 \text{ t}\cdot\text{h}^{-1}$ and the target for the resource of $40 \text{ mg}\cdot\text{L}^{-1}$ is $151.4 \text{ t}\cdot\text{h}^{-1}$ ($80+63.64+7.79=151.4$). The flow rates of the 100% fresh resource stream and the resource stream of $40 \text{ mg}\cdot\text{L}^{-1}$ included in the target calculation are shadowed in Table 5.

3.3 Example 3

This example has three external fresh resources: a resource of 100% purity with infinite amount, a resource of $30 \text{ mg}\cdot\text{L}^{-1}$ impurity with flow rate of $50 \text{ t}\cdot\text{h}^{-1}$, and a resource of $25 \text{ mg}\cdot\text{L}^{-1}$ impurity with infinite amount. Table 6 lists the original data for this example. Table 7 lists the generated data for this example.

Table 6 Original data for Example 3

Demand		Source	
$C_d/\text{mg}\cdot\text{L}^{-1}$	$F_d^R/\text{t}\cdot\text{h}^{-1}$	$C_s/\text{mg}\cdot\text{L}^{-1}$	$F_s^R/\text{t}\cdot\text{h}^{-1}$
0	12.5	0	
0	20	25	
0	16.67	30	50
25	36.36	80	12.5
25	44.31	100	20
40	30	120	16.67
50	60	80	36.36
75	88.89	90	44.31
25	22.86	90	30
75	133.33	100	60
120	100	120	88.89
200	18	200	22.86
75	88.89	150	133.33
150	43.33	200	100
200	5	300	18
50	40	300	88.89
400	12.5	300	43.33
400	70	600	5
600	10.2	800	40
800	4	800	12.5
		500	70
		850	10.2
		950	4

Table 7 Generated data for Example 3

Demand		Source	
$C_d/\text{mg}\cdot\text{L}^{-1}$	$F_d^R/\text{t}\cdot\text{h}^{-1}$	$C_s/\text{mg}\cdot\text{L}^{-1}$	$F_s^R/\text{t}\cdot\text{h}^{-1}$
0	49.17	0	
25	103.53	25	
40	30	30	50
50	100	80	48.86
75	311.11	90	74.31
120	100	100	80
150	43.33	120	105.56
200	23	150	133.33
400	82.5	200	122.86
600	10.2	300	150.22
800	4	500	
			70
		600	5
		800	52.5
		850	10.2
		950	4

In Table 7, the data of the demand and source streams are arranged in ascending order of their concentrations, respectively. From Table 7, it can be seen that the first demand stream needs hundred-percent fresh-resource only. For the demand stream of $25 \text{ mg}\cdot\text{L}^{-1}$, it can be satisfied by the external source of $25 \text{ mg}\cdot\text{L}^{-1}$. For the demand stream of $40 \text{ mg}\cdot\text{L}^{-1}$, its HCS and LCS are the sources of $80 \text{ mg}\cdot\text{L}^{-1}$ and $30 \text{ mg}\cdot\text{L}^{-1}$, respectively. DSR can be calculated from Eq. (10):

$$\begin{aligned}
 \text{DSR} &= \min \left[\frac{30}{80-30}, \frac{48.86}{40-30}, \frac{50}{80-40} \right] \\
 &= \min [0.6, 4.88, 1.25] \\
 &= 0.6
 \end{aligned}$$

Then the demand stream is the determining-stream. The amounts of the non-determining-streams can be calculated as follows:

$$F_{\text{sh},3} = \text{DSR} \times (C_d - C_{\text{sl}}) = 0.6 \times (40 - 30) = 6 \text{ t}\cdot\text{h}^{-1}$$

$$F_{\text{sl},3} = F_{\text{d},3} - F_{\text{sh},3} = 30 - 6 = 24 \text{ t}\cdot\text{h}^{-1}$$

The remainder amounts of the non-determining-streams of the source of $80 \text{ mg}\cdot\text{L}^{-1}$ and $30 \text{ mg}\cdot\text{L}^{-1}$ are:

$$F_{\text{sh},4}^R = F_{\text{sh},3}^R - F_{\text{sh},3} = 48.86 - 6 = 42.86 \text{ t}\cdot\text{h}^{-1}$$

$$F_{\text{sl},4}^R = F_{\text{sl},3}^R - F_{\text{sl},3} = 50 - 24 = 26 \text{ t}\cdot\text{h}^{-1}$$

In the next step, the HCS and LCS for the demand stream of $50 \text{ mg}\cdot\text{L}^{-1}$ are the sources of $80 \text{ mg}\cdot\text{L}^{-1}$ and $30 \text{ mg}\cdot\text{L}^{-1}$, respectively. Similar procedures can be carried out for this step.

Now as the external resource of $30 \text{ mg}\cdot\text{L}^{-1}$ is used up, the LCS will be the infinite external resource of $25 \text{ mg}\cdot\text{L}^{-1}$. For the demand streams of $150 \text{ mg}\cdot\text{L}^{-1}$, $200 \text{ mg}\cdot\text{L}^{-1}$, $600 \text{ mg}\cdot\text{L}^{-1}$ and $800 \text{ mg}\cdot\text{L}^{-1}$, they will be satisfied by the internal sources without using the external resource. Table 8 lists the matched data and factual data of the demand, the HCS and LCS streams. The determining-stream for each step is printed in bold in Table 8.

Table 8 The matched data of the demand, HCS and LCS streams for Example 3

$C_d/\text{mg}\cdot\text{L}^{-1}$	$F_d/\text{t}\cdot\text{h}^{-1}$	$F_d^R/\text{t}\cdot\text{h}^{-1}$	$C_{sh}/\text{mg}\cdot\text{L}^{-1}$	$F_{sh}/\text{t}\cdot\text{h}^{-1}$	$F_{sh}^R/\text{t}\cdot\text{h}^{-1}$	$C_{sl}/\text{mg}\cdot\text{L}^{-1}$	$F_{sl}/\text{t}\cdot\text{h}^{-1}$	$F_{sl}^R/\text{t}\cdot\text{h}^{-1}$
0	49.17	49.17				0	49.17	
25	103.53	103.53				25	103.53	
40	30	30	80	6	48.86	30	24	50
50	43.33	100	80	17.33	42.86	30	26	26
50	56.17	56.67	80	25.53	25.53	25	30.64	
50	0.5	0.5	90	0.19	74.31	25	0.31	
75	96.35	311.11	90	74.12	74.12	25	22.23	
75	120	214.76	100	80	80	25	40	
75	94.76	94.76	120	49.87	105.56	25	44.89	
120	55.68	100	120	55.68	55.68			
120	44.32	44.32	150	33.68	133.33	25	10.64	
150	43.33	43.33	150	43.33	99.65			
200	23	23	200	23	122.86			
400	82.5	82.5	500	55	70	200	27.5	99.86
600	5	10.2	600	5	5			
600	5.2	5.2	800	1.73	52.5	500	3.47	15
800	4	4	800	4	50.77			

From the data in Table 8, it can be seen that the concentration of the pinch-causing source for the 100% purity fresh resource is $0 \text{ mg}\cdot\text{L}^{-1}$, because the fresh resource is only used in Step (1). The pinch-causing source for the impure resource of $25 \text{ mg}\cdot\text{L}^{-1}$ is $150 \text{ mg}\cdot\text{L}^{-1}$. The minimum fresh resource consumption target of the 100% purity fresh resource is $49.17 \text{ t}\cdot\text{h}^{-1}$, and that of the resource of $25 \text{ mg}\cdot\text{L}^{-1}$ will be:

$$103.53 + 30.64 + 0.31 + 22.23 + 40 + 44.89 + 10.64 = 252.2 \text{ mol}\cdot\text{s}^{-1}$$

where the flow rates of the impure resource of $25 \text{ mg}\cdot\text{L}^{-1}$ included in the target calculation are shadowed in Table 8.

Figure 5 shows the shifted composite curves for Example 3. A design of the network is shown in Fig. 6. For this example, the resources of $0 \text{ mg}\cdot\text{L}^{-1}$ and $25 \text{ mg}\cdot\text{L}^{-1}$ have their pinch points, because their amounts are infinite. The external source of $30 \text{ mg}\cdot\text{L}^{-1}$ has no

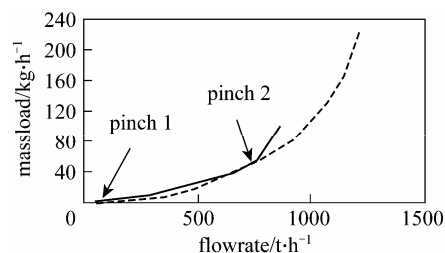


Figure 5 The shifted source/demand composite curves for Example 3

— demand; ---- source

pinch point due to its limited amount. The concentration of the pinch-causing source of the resource of $0 \text{ mg}\cdot\text{L}^{-1}$ is below $25 \text{ mg}\cdot\text{L}^{-1}$, the concentration of another infinite resource.

4 DISCUSSION

From the illustrated examples, it can be seen that the procedure proposed can be used for design and targeting the resource networks with multiple resources effectively. Compared to the graphical methods [13, 14], the method proposed in this work is a numerical one. Compared to the method of numerical method of Foo [15], the method proposed in this work is much simpler because the water cascade analysis technique [4] is tedious, as pointed out by Foo *et al* [30]. For a network with multiple resources, there might be many different designs with the same resources consumption. The method proposed in this work can provide one of the designs. The approach proposed by Prakash and Shenoy [31] can be used to generate alternative designs from the design obtained.

5 CONCLUSIONS

In this paper, a new method is proposed to design the networks with multiple resources of different qualities. The pinch points and targets of the minimum consumptions of the resources can be determined simultaneously in the design procedure. Compared to the networks with single resource, the networks with multiple resources often have special features. For a network of single resource with single contaminant, there is often only one pinch point for the resource. On the other hand, for a network of multiple resources with single contaminant, there might be a few different pinch points. Each resource might have its own pinch point, if its amount is sufficient. The contaminant concentration of the pinch-causing source for a resource will be below that of the higher-concentration resource(s).

From the examples investigated, it can be seen that the design procedure proposed is easy to use. The other important issues in the networks, such as minimum piping, minimum total cost, *etc.*, will be addressed in the future work.

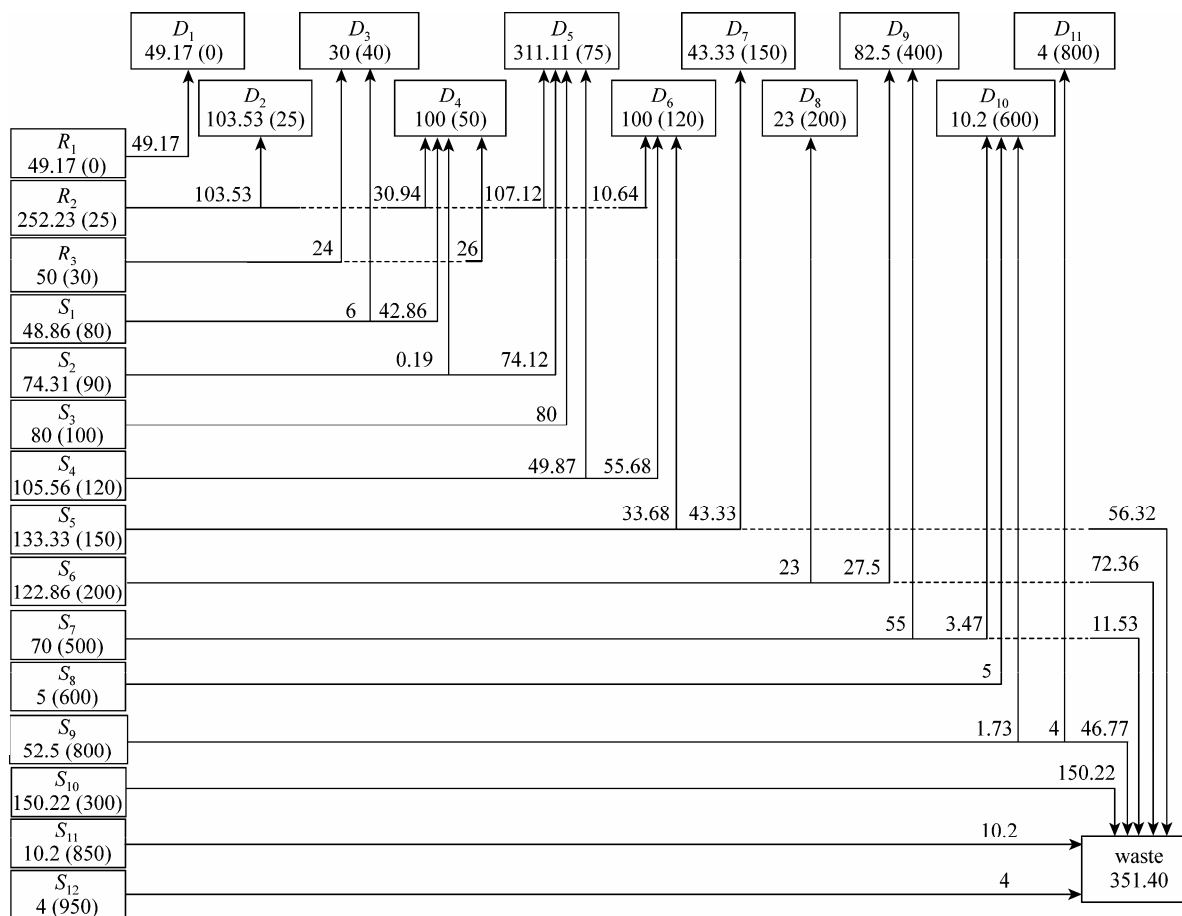


Figure 6 The structural design for Example 3 (The values show flow rate in $\text{t}\cdot\text{h}^{-1}$ with contaminant concentrations in $\text{mg}\cdot\text{L}^{-1}$ within braces)

NOMENCLATURE

C_d	concentration of the demand stream
C_{sh}	concentration of the HCS
C_{sl}	concentration of the LCS
D	demand
$F_{d,i}$	matched flow rate of the demand stream of step i
$F_{d,i}^R$	factual flow rate of the demand stream of step i
$F_{sh,i}$	matched flow rate of the HCS of step i
$F_{sh,i}^R$	factual flow rate of the HCS of step i
$F_{sl,i}$	matched flow rate of the LCS of step i
$F_{sl,i}^R$	factual flow rate of the LCS of step i
R	resource
S	source

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