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A Modified Method for Design of Distributed Wastewater Treatment Systems: Each Unit Removing Multiple Contaminants

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A modified method is presented for the design of distributed wastewater treatment systems, in which each process can remove multiple contaminants, based on our previous work. In the design procedure, the value of Total Mixing Influence Potential (TMIP), which can be obtained based on the pinch principle, reflects the influence of performing a process on the total treatment flowrate of the system. The process with the smallest TMIP value will be performed first, when designing of the treatment system. However, when a process can remove multiple contaminants, it is difficult to obtain the values of the TMIP. This paper improves the calculation of TMIP values for the processes, which can remove multiple contaminants, by combining pinch principle with a linear programming approach. The investigation of a literature example shows that the result obtained with the method proposed is comparable to the optimal solution obtained in the literature. In addition, the method proposed is low computational complexity and of clear engineering insight.

1. Introduction

Developing advanced wastewater treatment systems is an effective way to reduce water pollution, which is threatening the health of humans and aggregating the shortage of water resource. Wang and Smith (1994) pointed out that the distributed treatment (also named decentralized treatment) can often result in lower costs than centralized treatment. In addition, Opher and Friedler (2016) drew a conclusion that the distributed urban wastewater treatment system is environmentally better than the centralized system by performing a Life Cycle Assessment.

This paper focuses on the wastewater treatment systems of multiple contaminants. Wang and Smith (1994) introduced Pinch Analysis method for the design of distributed wastewater treatment systems. Kuo and Smith (1997) improved the method of Wang and Smith (1994) mainly by addressing the important features of multiple treatment units and by developing a staged design approach for multiple contaminant systems. Soo et al. (2013) extended the Wastewater Composite Curve proposed by Ng et al. (2007) to the synthesis of distributed wastewater treatment systems of one or two contaminants with multiple treatment units. In general, the Pinch Analysis method is conceptually clear and suitable for the systems of single contaminant or simple ones of multiple contaminants.

Mathematical programming method is the major tool for the integration of distributed wastewater treatment systems of multiple contaminants. Takama et al. (1980) initiated the study of water allocation network optimization with nonlinear programming (NLP) approach. However, they failed to obtain the global optimal solution. Later, many solving strategies, successive relaxed solution (Galan and Grossmann, 1998), superstructure decomposition and parametric optimisation strategies (Hernandez-Suarez et al., 2004), two-stage strategy (Castro et al., 2007), discretization optimal approach (Burgara-Montero et al., 2012), were presented for acquiring the global optimal solution of the system. Kollmann et al. (2014) discussed the energy potential of wastewater treatment plants which has yet unexploited. Alnouri et al. (2015) integrated on-site decentralized and off-site central treatment systems into the synthesis of industrial city water networks. Sueviriyapan et al. (2016) proposed a retrofit method for existing complex industrial wastewater systems by means of recycling and rerouting. Although mathematical programming approach is robust in handling complex systems, it is often computational complexity and lack of clear engineering insights.

To reduce the solving difficulty and provide clear engineering insights for the synthesis of distributed wastewater treatment systems of multiple contaminants, Li et al. (2015) proposed the concept of Total Mixing Influence Potential (TMIP) and develop a design procedure based on the concept. The system Li et al. (2015) considered is that the main task of a process is to remove only one contaminant (the contaminant is called as the main contaminant of the process, Liu et al., 2013) based on the pinch principle. However, in industrial cases, one treatment process can usually remove multiple contaminants. As mentioned above, it is difficult to deal with the systems of multiple contaminants with pinch method. This paper will provide the calculation of TMIP values for the processes which have multiple main contaminants by combining the pinch method with a linear programming (LP) approach.

2. The concept of Total Mixing Influence Potential (TMIP)

It is important to determine the preference order of treatment processes because unnecessary stream mixing caused by unreasonable performing order would reduce the contaminant concentrations and consequently increase the flowrates of downstream processes (Kuo and Smith, 1997). Based on this insight, Li et al. (2015) introduced the concept of TMIP to identify the reasonable performing order of treatment processes.

The definition of TMIP is shown in Eq(1) and Eq(2). In the *j*th column vector of Eq (1), which is referred to as Mixing Influence Treatment Flowrate (MITF) matrix, F_{TPj} is the minimum treatment flowrate of treatment process TP_j and the other elements are those of its downstream processes, where NT is the number of treatment processes. The sum of all the elements in the *j*th column vector, as shown in Eq (2), can reflect the influence of performing TP_j on the total treatment flowrate of the system and defined as Total Mixing Influence Potential (TMIP). The process with the minimum TMIP value should be performed first.

$$\begin{bmatrix} F_{TP1} & \cdots & MI_{j,1} & \cdots & MI_{NT,1} \\ \vdots & & \vdots & & \vdots \\ MI_{1,j} & \cdots & F_{TPj} & \cdots & MI_{NT,j} \\ \vdots & & \vdots & & \vdots \\ & \cdots & MI_{j,k} & \cdots & \\ \vdots & & \vdots & & \vdots \\ MI_{1,NT} & \cdots & MI_{j,NT} & \cdots & F_{TP_{NT}} \end{bmatrix} \tag{1}$$

$$MI_j = \sum_{i=1}^{NT} MI_{j,i} \tag{2}$$

3. The calculation of TMIP value for a process removing multiple contaminants

It can be seen from Eq(1) and Eq(2) that the calculation of TMIP value is essentially based on the minimum treatment flowrates of treatment processes. The minimum treatment flowrates for the processes which remove only one contaminant can be obtained with pinch principle (Li et al., 2015). To obtain the minimum treatment flowrates for the processes which can remove multiple contaminants, an LP approach is needed to be combined with the pinch method, which will be discussed in the following.

3.1 The minimum treatment flowrate for a process removing multiple contaminants

Let us denote the set of main contaminants of TP_j as $\mathbf{C_{TPj}}$, for example, $\mathbf{C_{TPj}}=\{A, B\}$. For removing contaminant *A*, the set of the streams to be treated by TP_j, $\mathbf{S_{TPj,A}}$, can be obtained with the pinch method of Li et al. (2015). Similarly, the set of the streams to be treated for removing contaminant *B*, $\mathbf{S_{TPj,B}}$, can be obtained. Then, in order to remove contaminants *A* and *B* simultaneously, the set of the streams that TP_j might treat is $\mathbf{S_{TPj}}= \mathbf{S_{TPj,A}} \cup \mathbf{S_{TPj,B}}$.

The minimum removal mass load for each main contaminant of TP_j ($M_{TPj,k}$) is shown in Eq(3), where F_i is the flowrate of wastewater stream S_i, $C_{i,k}$ is the concentration of contaminant *k* in S_i, $C_{env,k}^{\lim}$ is the environmental limit concentration of contaminant *k*, and $RR_{j,k}$ is the removal ratio of TP_j for contaminant *k*.

$$M_{TPj,k} = \frac{\sum_{i \in \boldsymbol{S_{TPj}}} F_i C_{i,k} - C_{env,k}^{\lim} \sum_{i \in \boldsymbol{S_{TPj}}} F_i}{RR_{j,k}} \quad k \in \boldsymbol{C_{TPj}} \tag{3}$$

The mass load removed by TP_j for each main contaminant should be equal to or higher than the corresponding minimum removal mass load, as shown in Eq (4), where $F_{TPj,i}$ is the flowrate of S_i to be treated by TP_j.

$$\sum_{i \in \boldsymbol{S_{TPj}}} F_{TPj,i} C_{i,k} \geq M_{TPj,k} \quad k \in \boldsymbol{C_{TPj}} \tag{4}$$

The constraint of flowrate of S_i to be treated by TP_j is:

$$0 \leq F_{TPj,i} \leq F_i \tag{5}$$

The objective is to obtain the minimum treatment flowrate of TP_j, which is the sum of flowrates of wastewater streams it should treat.

$$\min \sum_{i \in \boldsymbol{S_{TPj}}} F_{TPj,i} \tag{6}$$

3.2 The design procedure

Based on the minimum treatment flowrate obtained above, the MITF matrix and the TMIP values of a system can be calculated easily. The detailed procedure can be referred to Li et al. (2015), which is summarized as follows:

(1) Identify the main contaminants and calculate the minimum treatment flowrate for each treatment process;

(2) Calculate the minimum treatment flowrates of downstream processes for each treatment process based on the streams after it is performed and list the MITF matrix;

(3) Calculate the TMIP value with Eq(2) for each treatment process and identify the first process to be performed;

(4) Return to step (1) to identify the next process based on the current streams till the removed mass load of each contaminant is equal to or larger than the corresponding minimum removal mass load shown in Eq (3).

4. Case study

The stream and treatment process data for this example taken from Castro et al. (2007) are shown in Table 1. Each process can remove two contaminants. The environmental limit for each contaminant is 100 ppm.

Table 1: The stream and treatment process data

(a) Stream data

Stream	Flowrate ($t \cdot h^{-1}$)	Concentration (ppm)					
		A	B	C	D	E	F
S_1	19	1,100	500	500	200	800	100
S_2	7	40	0	100	300	910	200
S_3	8	200	220	200	500	150	0
S_4	6	60	510	500	200	780	100
S_5	17	400	170	100	300	900	0

(b) Treatment process data

Process	Removal ratio (%)					
	A	B	C	D	E	F
TP_1	99	99				
TP_2			99	99		
TP_3					99	99

The design procedure is as follows:

1. Identifying the main contaminants and calculating the minimum treatment flowrate for each process

Let us take process TP_1 as an example. It can be seen from Table 1(b) that TP_1 is required to remove contaminants A and B, i.e., $\boldsymbol{C_{TP1}}$={A, B}. For removing contaminant A, the set of the streams that TP_1 should treat is {S_1, S_5} and the minimum treatment flowrate is 27.96 $t \cdot h^{-1}$, which can be obtained based on pinch method shown in Table 2. Similarly, for removing contaminant B, the set of the streams that TP_1 should treat is {S_4, S_1} and the minimum treatment flowrate is 23.13 $t \cdot h^{-1}$, as shown in Table 3. For removing contaminants

A and *B* simultaneously, TP_1 might treat streams S_1, S_4 and S_5. The minimum treatment flowrate of TP_1 can be obtained by solving Formula (7).

Table 2: The minimum treatment flowrate of TP_1 for removing contaminant A

Stream	$C_{i,A}$ (ppm)	F_i (t·h^{-1})	$M_{i,A}$ (g·h^{-1})	$\sum M_{i,A}$ (g·h^{-1})	$F_{TP1,A}$ (t·h^{-1})
S_1	1,100	19	20,900	20,900	19
S_5	400	17	6,800	27,700	8.96
S_3	200	8	1,600	29,300	
S_2	40	7	280	29,580	
S_4	60	6	360	29,940	
Sum		57	29940		27.96

The streams printed in bold and italics are those TP_1 should treat for removing contaminant *A*

Table 3: The minimum treatment flowrate of TP_1 for removing contaminant B

Stream	$C_{i,B}$ (ppm)	F_i (t·h^{-1})	$M_{i,B}$ (g·h^{-1})	$\sum M_{i,B}$ (g·h^{-1})	$F_{TP1,B}$ (t·h^{-1})
S_4	510	6	3,060	3,060	6
S_1	500	19	9,500	12,560	17.13
S_3	220	8	1,760	14,320	
S_5	170	17	2,890	17,210	
S_2	0	7	0	17,210	
Sum		57	17210		23.13

The streams printed in bold and italics are those TP_1 should treat for removing contaminant *B*

$$\begin{cases} \min\left(F_{TP1,1}+F_{TP1,4}+F_{TP1,5}\right) \\ 1100F_{TP1,1}+60F_{TP1,4}+400F_{TP1,5} \geq \left(29940-57\times 100\right)/0.99 \\ 500F_{TP1,1}+510F_{TP1,4}+170F_{TP1,5} \geq \left(17210-57\times 100\right)/0.99 \\ 0 \leq F_{TP1,1} \leq 19 \\ 0 \leq F_{TP1,4} \leq 6 \\ 0 \leq F_{TP1,5} \leq 17 \end{cases} \tag{7}$$

It can be obtained from Formula (7):

$$\begin{cases} F_{TP1,1}=19\ \mathrm{t\cdot h^{-1}} \\ F_{TP1,4}=1.24\ \mathrm{t\cdot h^{-1}} \\ F_{TP1,5}=8.78\ \mathrm{t\cdot h^{-1}} \end{cases}$$

F_{TP1} = 19+1.24+8.78 = 29.02 t·h^{-1}. Similarly, the minimum treatment flowrates of other processes can be obtained, as listed in Table 4.

Table 4: The minimum treatment flowrate of each process

Process	Main contaminants	Streams treated	F_{TP1} (t·h^{-1})
TP_1	A, B	S_1, S_4, S_5	29.02
TP_2	C, D	S_1, S_3, S_4, S_5	35.49
TP_3	E	S_1, S_2, S_4, S_5	43.71

2. Determining the first process to be performed

Let us take $MI_{1,2}$ as an example to illustrate the calculation of MITFs. When TP_1 is performed, according to the results of Step 1, the streams after TP_1 can be shown in Figure 1. Based on the streams in Figure 1, the minimum treatment flowrate of TP_2 for removing contaminants *C* and *D* can be obtained as 35.49 t·h^{-1}, which is the value of $MI_{1,2}$ according to the definition of the MITF. Similarly, we can obtain other elements of MITF matrix. The MITF matrix is shown in Eq(8) and the TMIP values for all the processes are shown in Eq(9).

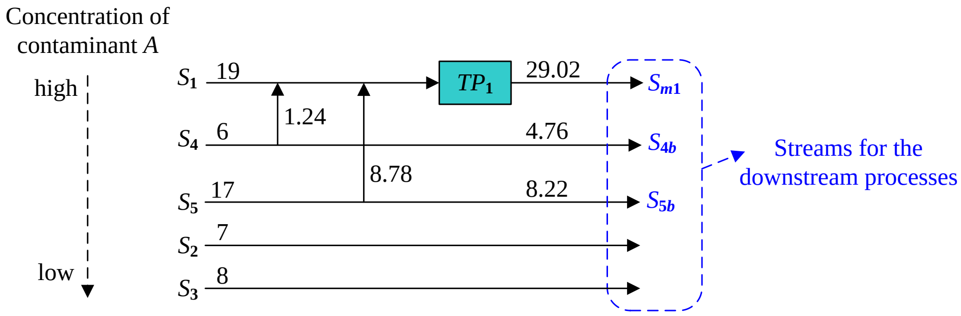

Figure 1: Streams after TP_1 for the downstream processes

$$\begin{bmatrix} F_{TP1} & MI_{2,1} & MI_{3,1} \\ MI_{1,2} & F_{TP2} & MI_{3,2} \\ MI_{1,3} & MI_{2,3} & F_{TP3} \end{bmatrix} = \begin{bmatrix} \boldsymbol{\mathit{29.02}} & 37.54 & 39.10 \\ 35.49 & 35.49 & 36.60 \\ 43.74 & 49.19 & 43.71 \end{bmatrix} \tag{8}$$

$$\begin{bmatrix} MI_1 & MI_2 & MI_3 \end{bmatrix} = \begin{bmatrix} \boldsymbol{\mathit{108.25}} & 122.22 & 119.41 \end{bmatrix} \tag{9}$$

It can be seen from Eq(9) that TP_1, whose TMIP value is the smallest, should be performed first (Li et al. 2015). The flowrate of TP_1 is 29.02 t·h^{-1}, which is the element of F_{TP1} in Eq(8) and printed in bold and italics.

3. Determining the second process to be performed

Obtain the MITFs for TP_2 and TP_3 based on the streams after TP_1, which have been shown in Figure 1. The MITF matrix for TP_2 and TP_3 is:

$$\begin{bmatrix} F_{TP2} & MI_{3,2} \\ MI_{2,3} & F_{TP3} \end{bmatrix} = \begin{bmatrix} 35.49 & \boldsymbol{\mathit{36.67}} \\ 49.21 & \boldsymbol{\mathit{43.74}} \end{bmatrix} \tag{10}$$

The TMIP values for TP_2 and TP_3 are:

$$\begin{bmatrix} MI_2 & MI_3 \end{bmatrix} = \begin{bmatrix} 84.70 & \boldsymbol{\mathit{80.41}} \end{bmatrix} \tag{11}$$

It can be seen from Eq(11) that the second process to be performed is TP_3 and the last one is TP_2. The flowrate of TP_3 is 43.74 t·h^{-1} and that of TP_2 is 36.67 t·h^{-1}, which are printed in bold and italics in Eq(10).

The total treatment flowrate is 29.02+43.74+36.67=109.43 t·h^{-1} and the final design is shown in Figure 2. The total treatment flowrate is very close to the global optimal solution of Castro et al. (2007), 109.401 t·h^{-1}, in which an LP formulation in the first stage is used to generate starting points for the solution of the NLP program in the second stage. The network interconnection number is also the same as the work of Castro et al. (2007). However, as can be seen from the above design procedure, the method proposed in this work is low calculation effort and of clear engineering insights.

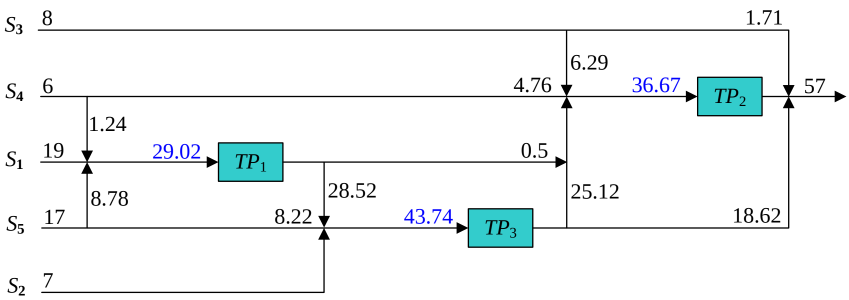

Figure 2: Design for the example

5. Conclusions

A modified method of Li et al. (2015) is presented for the design of distributed wastewater treatment systems, in which each process can remove multiple contaminants. The value of Total Mixing Influence Potential (TMIP), which can reflect the influence of performing a process on the total treatment flowrate of a system, is obtained by combining the Pinch Method with a linear programming approach. In the design procedure, the treatment process with the smallest TMIP value will be performed first. It is shown that the value of TMIP is a good indicator for determining the preference order of treatment processes. The method proposed is low computational complexity and of clear engineering insights. The investigation of a literature example shows that the results obtained with the method proposed is very close to the global optimal solution obtained with mathematical programming method.

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