

Article

A heuristic design method for batch water-using networks of multiple contaminants with regeneration unit[☆]

Aihong Li¹, Changzhan Liu¹, Zhiyong Liu^{2,*}

¹ Department of Chemical Engineering, Chengde Petroleum College, Chengde 067000, China

² School of Chemical Engineering, Hebei University of Technology, Tianjin 300130, China



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ABSTRACT

This work develops a heuristic method for the design of batch water-using networks of multiple contaminants with regeneration unit based on the concepts of concentration potential. A water-using network involving regeneration unit can be formed by adding the regenerated stream(s) into the network involving reuse only. In the design procedure of the network operated in a single batch mode, time is taken as the primary factor and concentration potentials as the secondary one. For the networks operated in a repeated mode, the design procedure is similar to that for continuous processes, besides designing the storage tanks with the rules proposed. Continuous regeneration unit is selected in this work. With the proposed method, the network structure corresponding to the minimum freshwater consumption can be obtained. It is shown that the method proposed in this article is simple, effective and has clear engineering meaning.

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1. Introduction

For the integration of water systems, most of the early research work focused on continuous processes. The main reason is that continuous processes consume much larger amount of freshwater and generate the corresponding amount of wastewater. In fact, it is also very important to develop water integration techniques for batch processes due to the following reasons [1]. First, batch processes are usually poorly designed for the lack of generic design methodology. Second, batch processes are becoming more active due to the growing demand for fine and special chemicals. Third, batch processes will generally produce more amount and higher toxicity wastewater than their continuous counterparts. In designing a continuous water-using system, contaminant concentration is the main constraint. In designing a batch one, apart from concentration constraint, time constraint needs to be considered simultaneously. Therefore, the research on the integration of batch water-using processes is more challenging than that of continuous processes. Regeneration units have commonly been introduced into continuous water networks for wastewater minimization [2]. It is essential to extend the approaches developed for the continuous water-using networks with regeneration units to batch processes. This work mainly discusses the integration techniques for water-using systems with regeneration unit in batch processes.

For the synthesis of continuous water-using networks, there are mainly two kinds of methods: pinch analysis methods and mathematical programming methods. For the systems discussed in this work, due to the inherent complexity in simultaneously considering both time and concentration constraints, as well as the introduction of regeneration unit, the pinch-based methods are not often used, even for the systems of single contaminant. Foo *et al.* [3] extended water cascade analysis technique, which was originally presented for targeting and designing continuous water networks [4], to batch total resource conservation networks.

Mathematical programming methods are the preferred design approaches for the batch water-using networks with regeneration unit. Liu *et al.* [5] proposed a superstructure for discontinuous water-using networks of single contaminant, in which one central continuous regeneration unit was involved. They established mathematical models under the framework of continuous time representation and presented a two-step solving strategy. Shoaib *et al.* [6] provided a three-stage procedure to sequentially minimize the consumption of freshwater, the number of tanks, and the number of network interconnections for the batch water systems of single contaminant. Finally, the placement of a regeneration unit was discussed based on the insights obtained from pinch analysis. Lee *et al.* [7] extended the work of Shoaib *et al.* [6] to the systems of multiple contaminants involving mass-transfer and non-mass transfer operations, in which the optimization procedure increased to four steps.

El-Halwagi and his coworkers initiated a property-based synthesis of water networks. For the synthesis of batch water networks with interception devices, Ng *et al.* [8] built a source-tank-interception-

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* Corresponding author.

E-mail address: liuzhiyong@hebut.edu.cn (Z. Liu).

tank-sink superstructure and formulated it as a mixed integer nonlinear programming (MINLP) model. By solving the model, they obtained a network with minimum total annualized cost. Chen *et al.* [9] presented a unified model for the synthesis of property-based batch and/or continuous resource conservation networks. In the model, the material reuse/recycle, interception, and waste treatment were all taken into consideration.

Tokos and Pintarič [10] optimized the water network of a brewery plant by installing on-site batch or semi-continuous regenerators based on the model of Kim and Smith [11]. Tokos *et al.* [12] extended the superstructure of Tokos and Pintarič [10] to total water network with changing daily production schedule. To solve the large-scale industrial problem, they presented two alternative multilevel strategies by means of temporal decomposition.

Adekola and Majozi [13] developed a method for wastewater minimization of multi-contaminant batch water networks with a regenerator. The method did not require the production schedule to be given beforehand. A two-step procedure proposed by Majozi and Gouws [14] was used to solve the MINLP model of the system. Dong *et al.* [15] presented a modified state-space superstructure for the synthesis of batch water networks with multiple regeneration modules. They adopted a rule-based solution strategy to reduce the computation complexity.

It can be seen from the above discussion that the research on the synthesis of batch water-using networks with multiple contaminants involving regeneration unit is relatively less than the research on that of continuous water-using networks. Mathematical programming methods were generally adopted to study this topic. However, the mathematical models established are usually very complex and global optimal solutions might not be guaranteed. If much simpler models are taken, although global optimal solutions might be obtained, the practical significance of the solutions will be weakened. The purpose of this article is to provide a design method which is simple and has clear engineering meaning for the batch water-using networks of multiple contaminants with regeneration unit. The new method is developed based on the concepts of concentration potential proposed by Liu *et al.* [16] for multi-contaminant water networks and a simple insight of Liu *et al.* [17] on the water systems involving regeneration units. Both Liu *et al.* [16,17] were originally proposed for continuous processes.

A batch plant can run in a single batch mode or in a repeated mode. For a system operated in a single batch mode, the wastewater produced at a later time cannot be reused by a process even if the concentration of the wastewater is lower than the limiting inlet concentration of the process [1]. Therefore, time should be taken as the primary factor and concentration as the secondary one. For a system operated in a repeated mode, the design procedure is similar to that for continuous processes, besides designing the storage tanks with the proposed rules. The continuous regeneration unit is selected in this work. Two examples will be investigated to show the design procedure proposed.

2. Problem Statement

Given are the following information: (i) the limiting inlet and outlet concentrations and the removed mass loads for every water-using process, (ii) the predetermined production schedule or the duration for every water-using process, (iii) the regeneration units running in continuous mode and being installed storage tanks before and after the regeneration units, and (iv) the regeneration units can be modeled by either the fixed regenerated concentration (RC) or the fixed removal ratio (RR) type.

Assume that: (i) the contaminant concentration of freshwater is zero, (ii) there is no water loss in water-using processes and regeneration units, and (iii) the maximum inlet concentrations of regeneration units are not constrained.

The objective is to (i) minimize the freshwater consumption, (ii) minimize the number and capacity of storage tanks, and (iii) determine the production schedule for water-using processes, if necessary.

3. The Concepts of Concentration Potential

Liu *et al.* [16] proposed the concepts of concentration potential based on the overall allocation possibility of source (outlet) streams to demand (inlet) streams analogous to the systems of single contaminant. The maximum quasi-allocation ratio $R_{i,j}$, defined in Eq. (1), reflects the possibility of 1 ton of demand D_j to reuse source S_i . The contaminant that determines the value of $R_{i,j}$ is called as the reuse key contaminant (RKC). The concentration potential of demand D_j , $CPD(D_j)$, is defined as Eq. (2) and the concentration potential of source S_i , $CPS(S_i)$, as Eq. (3).

$$R_{i,j} = \min_{k=1,2,\dots,NC} \left(\frac{C_{D_j,k}^{\text{lim}}}{C_{S_i,k}} \right) = \frac{C_{D_j,RKC}^{\text{lim}}}{C_{S_i,RKC}} \quad (1)$$

$$CPD(D_j) = \sum_{i=1}^{NS} R_{i,j} \quad (2)$$

$$CPS(S_i) = \frac{1}{\sum_{j=1}^{ND} R_{i,j}} \quad (3)$$

where $C_{D_j,k}^{\text{lim}}$ is the limiting concentration of contaminant k in D_j , $C_{S_i,k}$ is the concentration of contaminant k in S_i , NC is the number of contaminants, NS is the number of source streams, and ND is the number of demand streams. For the water-using networks operated in a single batch mode, the time nature dictates $i \neq j$ (i.e., there is no stream recycle) in Eqs. (2) and (3). For the batch water-using networks operated in a repeated mode, this constraint can be omitted.

The order of concentration potentials agrees with that of conventional concentrations [16]. In the design procedure, the value of CPD will be used as an important factor in identifying the precedence order of the processes. The value of CPS will be used as an indicator to select the sources to be regenerated.

Li *et al.* [18] applied the concentration potential concepts to the design of batch water-using networks involving reuse only. By manual calculation, Li *et al.* [18] obtained the results that are comparable to those obtained by mathematical programming methods.

4. Design Procedure for the Water-using Networks Operated in a Single Batch Mode

For the water-using networks with regeneration units, Liu *et al.* [17] obtained an insight that the difference between a network involving regeneration reuse and a network involving reuse only is that there is one or a few additional sources, the regenerated streams, in the former network. If the flow rates and concentrations of the regenerated streams can be determined and the regenerated streams are added into the network involving reuse only, the network involving regeneration reuse can be formed and then be designed with the methods proposed for the network involving reuse only. This insight has been applied to the design of continuous water networks involving regeneration reuse [17], regeneration recycling [19], the regeneration recycling systems with internal water mains [20], and the hydrogen systems involving regeneration reuse [21]. In addition, the insight contributed to solving the MINLP model formulated for the water networks involving regeneration reuse/recycling [22].

In this section, a three-step procedure based on the insight of Liu *et al.* [17] will be introduced to design a water-using network operated in a single batch mode. The network involving reuse only is first designed. Then, the flow rate and concentrations of the regenerated

stream are estimated. Finally, the design of the network involving regeneration reuse can be obtained.

4.1. Designing the network involving reuse only

4.1.1. Determination of the precedence order of water-using processes

The schedule-related constraint should be given higher priority in determining the precedence order of the processes for the integration of a water-using network operated in a single batch mode. The processes will be performed in the order of their start moments.

- If the production schedule is given, the precedence order can be determined by the start moments of processes directly.
- If the production schedule needs to be assigned according to the principle of maximizing wastewater reuse, such as Example 1, the precedence order should be determined by combining the start moments and the CPD values.

To be specific, when a few processes can be performed within the same time period, the process with the lowest CPD value is performed first. Furthermore, if several processes have the same CPD values, the process with the lowest CPS value will be performed first to provide high-quality internal source (outlet stream of a process) for the downstream processes [16].

4.1.2. Allocation of source streams to demand streams

Similar to the determination of precedence order, time has priority in allocating source streams to demand streams as well.

- Only the sources produced before the start moment of a process can be listed as the reuse candidates for the process. Before the first internal source is produced, only freshwater can be used. The minimum freshwater consumption for satisfying demand D_j is calculated with Eq. (4), where m_k^{rem} is the removed mass load of contaminant k in D_j and $C_k^{lim, out}$ is the limiting outlet concentration of contaminant k in D_j . The contaminant that determines the value of F_{fresh}^{min} is called as the freshwater key contaminant (FKC) [16].

$$F_{fresh}^{min} = \max_{k=1,2,\dots,NC} \left(\frac{m_k^{rem}}{C_k^{lim, out}} \right) \quad (4)$$

- When the time constraint can be met, the allocation rules of source streams to demand streams in designing batch networks involving regeneration reuse are identical to those in continuous networks [19]. They are briefly stated as follows:
 - When satisfying D_j , the source with the largest R_{ij} value should be reused first. If a few sources have the same R_{ij} value, the source with the largest CPS value should be used to save the freshwater consumption of downstream processes.
 - If the RKC and the FKC are the same contaminant, and the concentration of this contaminant in a source is not lower than the limiting outlet concentration of D_j , the source should not be reused and freshwater is used solely, because the freshwater consumption cannot be reduced by reusing the source [16].
 - If a few sources meet the condition of $R_{ij} > 1$, reuse the source with sufficient flow rate. This can simplify the network structure.
 - When D_j cannot be satisfied by one single source, select the next one according to the same rules, till D_j is satisfied totally.

4.1.3. Design of storage tanks for reuse

If source S_i is selected to satisfy demand D_j and the discharge moment of S_i does not coincide with the charge moment of D_j , a storage

tank is required to meet the time constraint. The design principle is to reduce the number and capacity of storage tanks.

- For a system with flexible production schedule, make the charge moment of D_j coincide with the discharge moment of S_i as much as possible.
- Use the shared tank, in other words, the tanks with non-overlapping storing period can be merged into one.
- Although a storage tank is not empty, if the original wastewater in the tank and the wastewater to be discharged to the tank will be reused to the same processes, they can certainly be mixed in the tank.

4.2. Estimating the flow rate and concentrations of regenerated stream

For the regeneration unit modeled as the fixed RC type, the regenerated concentrations are known, and the flow rate of regenerated stream will be determined as discussed in Section 4.3. For the regeneration unit modeled as the fixed RR type, the flow rate and concentrations of regenerated stream need to be estimated before iteration.

To estimate the flow rate and concentrations of regenerated stream in a continuous water network, Liu et al. [17] divided the whole network into the subnetwork before regeneration and that after regeneration according to the concentration characteristics of water-using processes. By designing the subnetwork before regeneration, the flow rate and concentrations of the regenerated stream can be obtained. Similar to the method of Liu et al. [17], this work divides the whole batch water network into the subnetwork before regeneration and that after regeneration, with time as the primary factor and concentration characteristics as the secondary factor.

In the design procedure, the sources are listed in the order of their production moments first. The processes ranking close to the top of the source-list are classified as the subnetwork before regeneration, and those close to the bottom as the subnetwork after regeneration. For a process in the middle of the source list, if its inlet concentrations are lower, it usually needs to use regenerated stream and therefore is classified as the subnetwork after regeneration; if its outlet concentrations are higher, it usually needs to be regenerated and therefore is classified as the subnetwork before regeneration. The division of subnetworks is shown in Fig. 1 and will be illustrated in detail in Example 1.

Then, the un-reused sources from subnetwork before regeneration are selected in the increasing order of CPS values. In the first iteration, the flow rate of the regenerated stream (F_{reg}^0) is unknown, the sources which are suitable for regeneration will be regenerated, with some “outlier” of high concentrations being excluded [19]. Then, the regenerated concentrations of contaminant k , $C_{reg, k}^0$, can be obtained with Eq. (5), where $C_{in, k}^0$ is the concentration of contaminant k at the inlet of regeneration unit.

$$C_{reg, k}^0 = C_{in, k}^0 \times (1 - RR_k) \quad (5)$$

4.3. Obtaining the network involving regeneration reuse

The network involving regeneration reuse can be formed by adding the regenerated stream into the internal sources. The subnetwork after regeneration should be redesigned with the method for the network involving reuse only described in Section 4.1. When iteration i is finished, if the consumption of regenerated stream, F_{reg}^i , is equal to or larger than F_{reg}^{i-1} , which means that the un-reused streams are fully utilized, the network obtained is the final design; if F_{reg}^i is less than F_{reg}^{i-1} , which means that the regeneration amount is surplus and might lead to higher regenerated concentrations, the freshwater consumption will therefore be increased. In this case, take the flow rate of regenerated

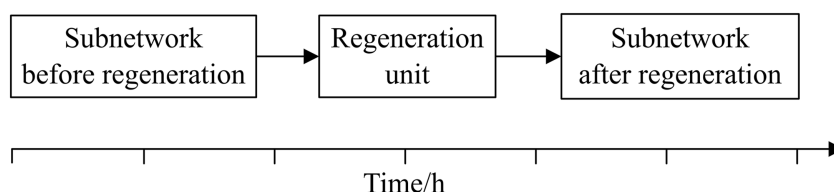


Fig. 1. The division of subnetworks for the water-using networks operated in a single batch mode.

stream obtained in the current iteration as F_{reg}^{i+1} , reselect the sources to be regenerated and do the next iteration, till F_{reg}^n is equal to or larger than F_{reg}^{n-1} . The design procedure discussed above is shown in Fig. 2.

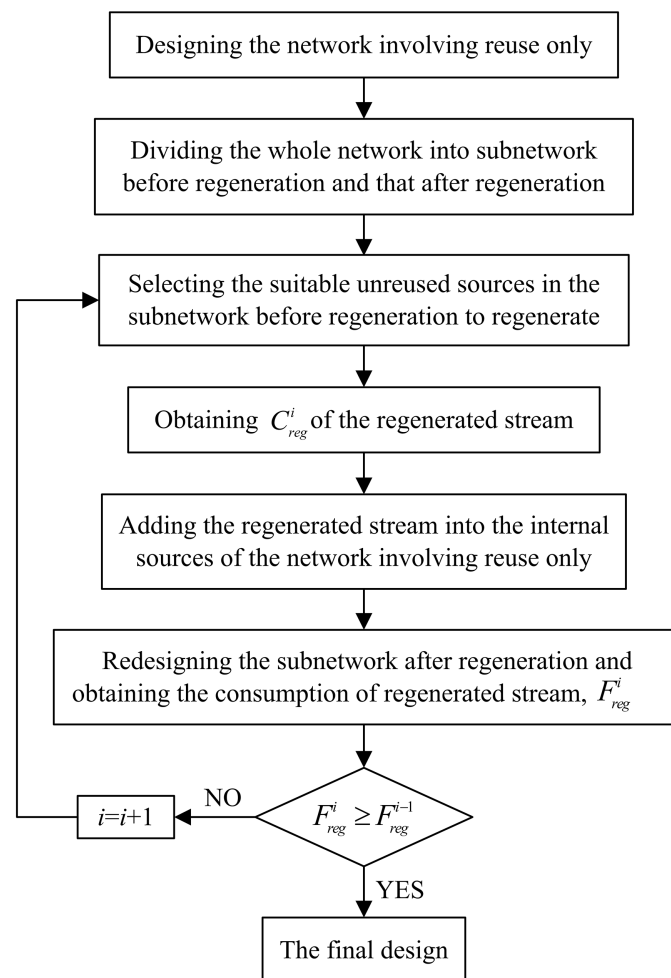


Fig. 2. Design procedure for the water-using networks operated in a single batch mode.

5. Design Procedure for the Batch Water-using Networks Operated in a Repeated Mode

Foo et al. [23] pointed out that wastewater can be reused between adjacent batches by intermediate storage tanks. Thus, the integration of the batch water-using networks operated in a repeated mode can be similar to that of continuous water networks. Based on the insight of Liu et al. [17], Pan et al. [19] proposed an iterative method to design the continuous water-using networks involving regeneration recycling. This article adopts the method of Pan et al. [19], combining the rules for setting storage tanks proposed in Section 4.1.3, to design the batch water-using networks operated in a repeated mode. The detailed procedure will be illustrated in Section 6.2.

6. Case Studies

6.1. Example 1

This example taken from Adekola and Majozzi [13] shows the design of the networks of flexible schedule and regeneration unit with fixed RR model. Four mixers produce products A, B, C and D, respectively. The production duration and the number of batches in 24 h (24 h is considered as a production cycle) are shown in Table 1. In this example, only the water used for washing mixers is considered. Once each batch of production has been completed, the washing of mixer to remove residual product (contaminant) takes 0.5 h. The charge and discharge of washing water are supposed to be finished instantly. The contaminant loads (M) and the limiting inlet and outlet concentrations are shown in Table 2. The RR values of regeneration unit for contaminants A, B, C and D are (95%, 99%, 96%, 98%), respectively.

Table 1
Production data for Example 1

Mixer	Product	Duration/h	Number of batches
1	A	7	2
2	B	5.5	3
3	C	11	1
4	D	11	2

Table 2
Limiting data for Example 1

Mixer	Contaminant	M/kg	$C_{lim,in}^{lim}/\text{mg}\cdot\text{kg}^{-1}$	$C_{lim,out}^{lim}/\text{mg}\cdot\text{kg}^{-1}$	F_{lim}^{lim}/kg
1	A	15	14000	40000	576.9
	B		0		
	C		7000		
	D		3500		
2	A	15	14000	45000	361.4
	B		3500		
	C		7000		
	D		7000		
3	A	30	14000	50000	697.6
	B		0		
	C		7000		
	D		3500		
4	A	70	14000	60000	1238.9
	B		0		
	C		7000		
	D		3500		

In this example, the different batches of the same product in 24 h are considered as the separate water-using processes. For example, there are processes $P_{1,1}$ and $P_{1,2}$ in Mixer 1, the inlet stream of $P_{1,1}$ is denoted as $D_{1,1}$ and the outlet stream as $S_{1,1}$. The design procedure is as follows.

6.1.1. Designing the network involving reuse only

Determine the start moment of every water-using process. Because the production schedule is not given directly, the boundaries of the start moment of every process need to be determined first based on the number of batches, the production duration and the washing duration. For example, in Mixer 1, as shown in Fig. 3, for $P_{1,1}$, the earliest

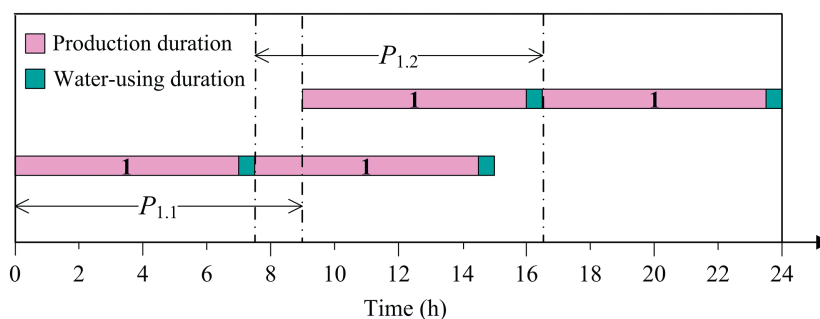


Fig. 3. The boundaries of the start moments of processes in Mixer 1 for Example 1.

start moment is 0.0 h and the latest start moment is 9.0 h; for $P_{1,2}$, the earliest start moment is 7.5 h and the latest start moment is 16.5 h. Similarly, the boundaries of the start moments of other processes can be determined, as listed in Table 3. Because water is only used for washing equipment in this example, the start moment of a process (e.g., 0.0 h for $P_{1,1}$) plus the production duration (7 h) is the water charge moment of the process (7.0 h), and continually plus the washing duration (0.5 h) is the water discharge moment (7.5 h).

Table 3
The boundaries of the start moments of processes for Example 1

Process	The lower boundary of the start moment/h	The upper boundary of the start moment/h
$P_{1,1}$	0.0	9.0
$P_{1,2}$	7.5	16.5
$P_{2,1}$	0.0	6.0
$P_{2,2}$	6.0	12.0
$P_{2,3}$	12.0	18.0
$P_{3,1}$	0.0	12.5
$P_{4,1}$	0.0	1.0
$P_{4,2}$	11.5	12.5

Determine the first process to be performed. It can be seen from Table 3 that $P_{1,1}$, $P_{2,1}$, $P_{3,1}$, and $P_{4,1}$ can be performed at 0.0 h. Therefore, the CPD values of the four demands need to be calculated. The CPD value of $D_{1,1}$ is the lowest, thus $P_{1,1}$ should be performed first. The freshwater consumption is 375 kg and the outlet concentrations are (40,000, 0, 0, 0) $\text{mg} \cdot \text{kg}^{-1}$.

Calculate the CPD values of $P_{2,1}$, $P_{3,1}$, and $P_{4,1}$ based on $S_{1,1}$. The values of the three processes are the same, thus their CPS values need to be calculated. Process $P_{3,1}$, whose CPS value is the smallest, should be the second process to be performed. Because the production duration of Mixer 3 (11 h) is longer than that of Mixer 1 (7 h), $D_{3,1}$ can reuse $S_{1,1}$ in terms of time. The flow rate of $D_{3,1}$ is determined by contaminant C, and the concentration of contaminant C in $S_{1,1}$ is 0 $\text{mg} \cdot \text{kg}^{-1}$. Therefore, the reuse amount of $D_{3,1}$ is the same as that when it only uses freshwater, i.e. 600 kg. The reuse amount of $S_{1,1}$ to $D_{3,1}$ is 210 kg, $D_{3,1}$ thus still consumes freshwater 390 kg.

Similar to $P_{3,1}$, $P_{4,1}$ is identified as the third process to be performed. It reuses the remnant $S_{1,1}$ (165 kg) and 163.3 kg of $S_{3,1}$, and consumes 838.4 kg of freshwater.

Process $P_{2,1}$ is obviously the fourth process. Now, the exact production schedule of the performed processes have been able to be determined. The latest start moment of $P_{2,1}$ is 6.0 h, as can be seen from Table 3. Correspondingly, the latest water-using moment of $P_{2,1}$ is 11.5 h (6.0 + 5.5 = 11.5). This moment should be set as the discharge moment of $P_{3,1}$ to facilitate the direct reuse of $S_{3,1}$ to $D_{2,1}$. It can be inferred that the water-using moment of $P_{3,1}$ is 11.0 h and the start performing moment is 0.0 h. According to the water-using moment

of $P_{3,1}$, combining with the stream allocation determined, the exact production schedule of the performed processes can be obtained: the discharge moment of $P_{1,1}$ is 11.0 h, and the water-using moment of $P_{4,1}$ is 11.5 h. In addition, it can be known from the performing moment of $P_{2,1}$ that the start moments of $P_{2,2}$ and $P_{2,3}$ are 12.0 and 18.0 h, respectively.

According to the above production schedule obtained, $D_{2,1}$ can reuse $S_{3,1}$ but cannot reuse $S_{4,1}$. Demand $D_{2,1}$ reuses 41.2 kg $S_{3,1}$ and consumes 292.1 kg freshwater.

The performing of the rest processes is similar to those discussed above. The network involving reuse only is shown in Fig. 4. The freshwater consumption is 3405.2 kg, which is 5.07% lower than the result (3587 kg) of Adekola and Majozzi [13].

The storage tanks for reuse needs to be designed. A tank (Tank 1) is required to store 165 kg of $S_{1,1}$ and drain it to $D_{4,1}$ at 11.5 h. Thus, Tank 1 is empty when $S_{3,1}$ is produced at 11.5 h. For $S_{3,1}$, a total of 245.7 kg needs to be stored and will be reused to $D_{2,2}$, $D_{1,2}$, $D_{4,2}$ and $D_{2,3}$ at 17.5, 22.5, 23.0 and 23.5 h, respectively. Similarly, Tank 2 can be designed for $S_{4,1}$. The water storage situation in Tanks 1 and 2 is shown in Fig. 4.

6.1.2. Designing the network involving regeneration reuse

Firstly, the whole network needs to be divided into the subnetwork before regeneration and that after regeneration. Table 4 lists the sources ranked in the order of their production moments: the processes listed close to the top of Table 4, $P_{1,1}$ to $P_{2,2}$, are classified into the subnetwork before regeneration and the rest into the subnetwork after regeneration. Then, the sources to be regenerated in the subnetwork before regeneration should be identified: $S_{1,1}$ has very low concentrations and has been reused totally; $S_{2,1}$ and $S_{2,2}$ should be discharged to the wastewater treatment system because they contain contaminant B which is not permitted at the inlet of other processes; thus, un-reused $S_{3,1}$ and $S_{4,1}$ are identified as the sources to be regenerated. The consumption of the regenerated stream is 1482.1 kg and the regenerated concentrations are (457, 0, 691, 913) $\text{mg} \cdot \text{kg}^{-1}$.

Add the above regenerated stream into the sources and redesign the subnetwork after regeneration. Demand $D_{1,2}$ is totally satisfied by the regenerated stream and the consumption is 379.3 kg. Demand $D_{4,2}$ reuses all of $S_{1,2}$ and 805.4 kg of regenerated stream. Demand $D_{2,3}$ reuses 34.4 kg of $S_{4,2}$, the remaining regenerated stream (297.4 kg), and still needs to consume 1.54 kg of freshwater. The regenerated stream being used up, the result obtained is the final design, as shown in Fig. 5. The final inlet and outlet concentrations in each mixer are shown in Table 5. The flow rate of regeneration unit is 61.754 $\text{kg} \cdot \text{h}^{-1}$. The freshwater consumption of the network involving regeneration reuse is 2150.2 kg, which is 18.97% lower than the result of Adekola and Majozzi [13] (2653.5 kg).

Compared to the network involving reuse only, the introduction of a regeneration unit with RR of (95%, 99%, 96%, 98%) reduces freshwater consumption by 36.85%. The comparison of the results obtained in this

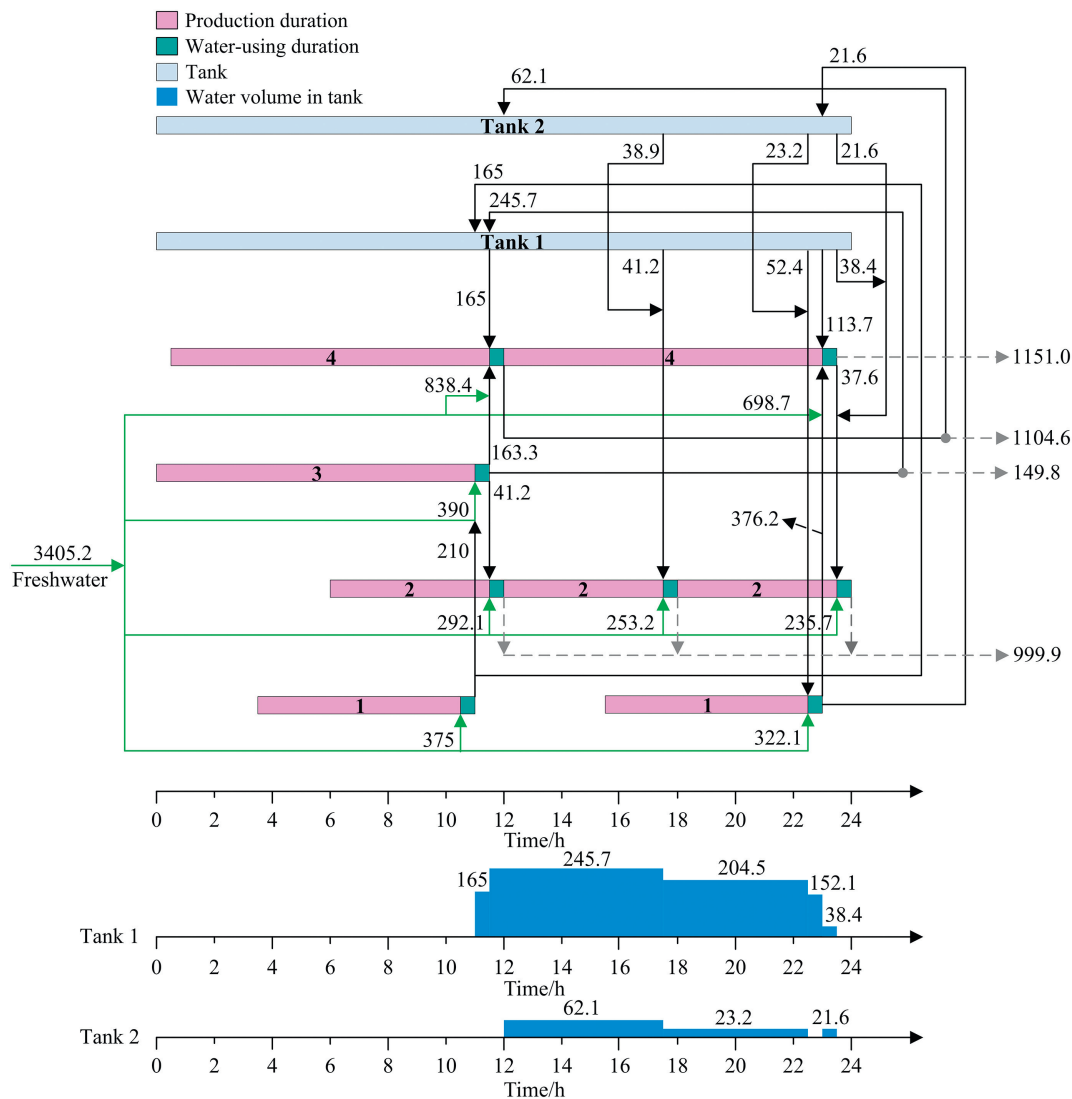


Fig. 4. The network involving reuse only for Example 1 (where the numbers are the amount of water in kg).

work and those of Adekola and Majozi [13] is listed in Table 6. The reasons why this work can reduce the consumption of freshwater is: (a) increasing the chance of direct reuse by adjusting the performing time of some processes, for example, arranging the discharge time of $P_{1,2}$ as the charge time of $P_{4,2}$ can reuse 379.3 kg $S_{1,2}$ to $D_{4,2}$; (b) saving high-quality sources for downstream processes, for example, reusing part of $S_{1,1}$ for $D_{3,1}$ and the reminder for $D_{4,1}$. It can be seen from the above design procedure that the method proposed is simple and effective.

Table 4
Division of subnetworks for Example 1

Subnetwork	Process	Production moment of source/h
Subnetwork before regeneration	$P_{1,1}$	11.0
	$P_{3,1}$	11.5
	$P_{4,1}$	12.0
	$P_{2,1}$	12.0
	$P_{2,2}$	18.0
Subnetwork after regeneration	$P_{1,2}$	23.0
	$P_{4,2}$	23.5
	$P_{2,3}$	24.0

6.2. Example 2

This example taken from Li *et al.* [18] is intended to illustrate the design of the networks of fixed production schedule and the regeneration unit with fixed RC model. The batch water network is operated in a repeated mode. The limiting data for one production cycle is listed in Table 7. Processes 1, 2, and 4 are fixed mass-load operations, and processes 3 and 5 are fixed flow rate operations. The regenerated concentrations are (40, 60, 20) $\text{mg} \cdot \text{kg}^{-1}$.

The design procedure is as follows.

Add the regenerated stream with concentrations of (40, 60, 20) $\text{mg} \cdot \text{kg}^{-1}$ into the internal sources. Calculate the CPD values and list the demands in the increasing order of CPD values, as shown in Table 8.

D_1 is satisfied first with 30 t of freshwater. Next, D_2 is satisfied with 75 t of regenerated water. The third demand, D_4 , is satisfied by 27.27 t of S_1 . The rest two demands, D_3 and D_5 , have the same CPD value. Because D_3 is performed before D_5 , D_3 is satisfied first by 40 t of S_2 . D_5 is satisfied by 2.73 t of remaining S_1 , 35 t of remaining S_2 and 2.72 t of S_4 . The freshwater consumption is 75 t and the final inlet and outlet concentrations are shown in Table 9.

The un-reused sources are listed in the increasing order of CPS values as: 40 t of S_3 , 40 t of S_5 , and 25 t of S_4 . The sources to be regenerated are 40 t of S_3 and 35 t of S_5 and the regeneration concentrations are

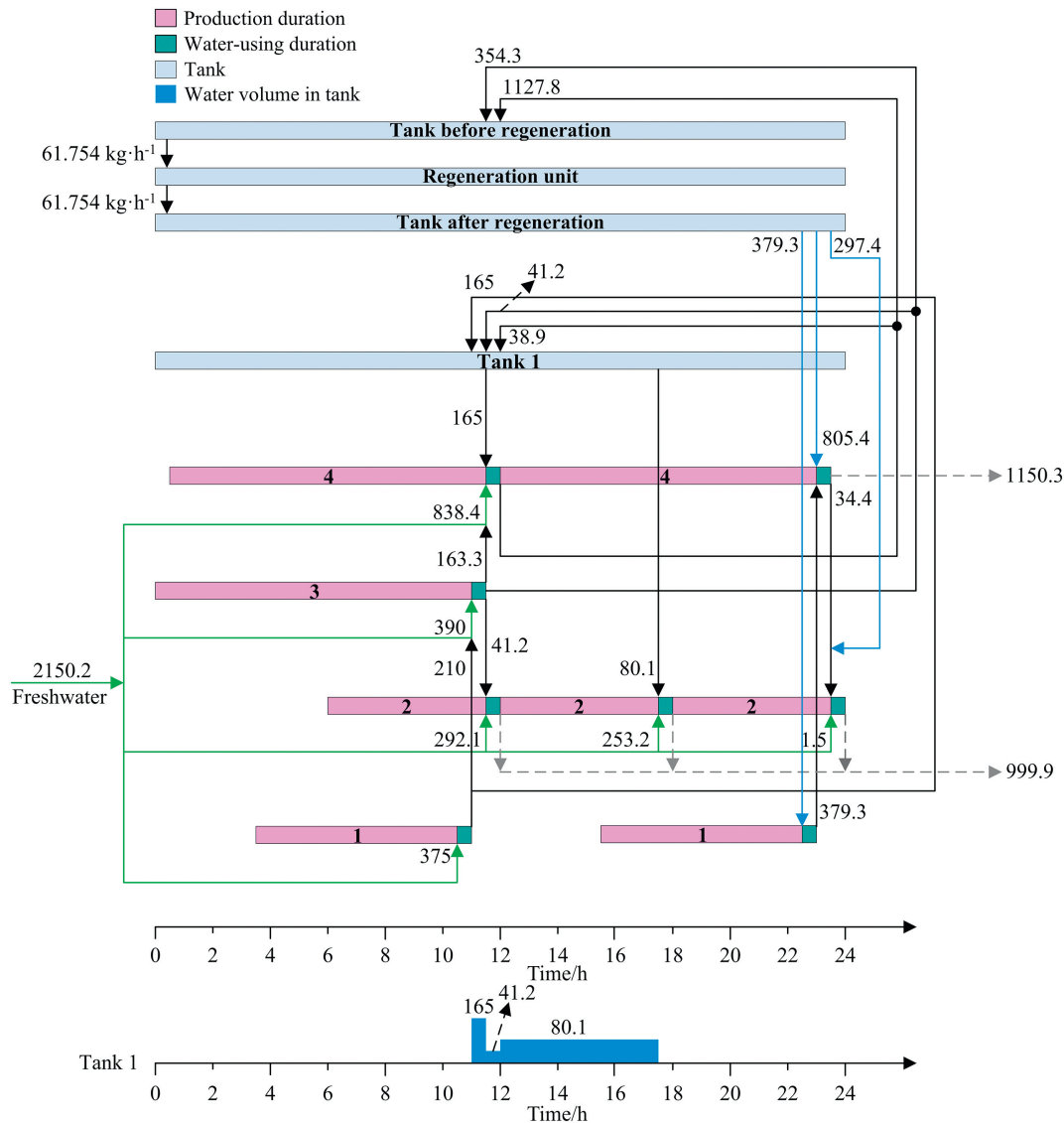


Fig. 5. The network involving regeneration reuse for Example 1 (where the numbers are the amount of water in kg).

Table 5

The final inlet and outlet concentrations in each mixer for Example 1

Process	$C^{in}/\text{mg}\cdot\text{kg}^{-1}$				$C^{out}/\text{mg}\cdot\text{kg}^{-1}$				F/kg
	A	B	C	D	A	B	C	D	
P_1	457	0	691	913	40000	0	691	913	379.3
P_2	1760	0	688	7000	1760	45000	688	7000	333.3
P_3	14000	0	0	0	14000	0	50000	0	600
P_4	13119	0	691	913	13119	0	691	60000	1184.7

The shadowed concentrations are those reaching their limiting values.

Table 6

Comparison of the results for Example 1

	Network involving reuse only		Network involving regeneration reuse		
	F_f/kg	Number of tanks	F_f/kg	F_{reg}/kg	Number of tanks
Adekola and Majoji [13]	3587	1	2653.5	1166.7	1
This work	3405.2	2	2150.2	1482.1	1

(150.00, 82.48, 70.58) $\text{mg}\cdot\text{kg}^{-1}$. The flow rate of regeneration unit is $8.824 \text{ t}\cdot\text{h}^{-1}$.

According to rules (b) and (c) described in Section 4.1.3, S_1 needs Tank 1 (T_1), S_2 and S_4 can share Tank 2 (T_2). The variations of water amount in T_1 and T_2 are shown in Fig. 6.

The final design of this example is shown in Fig. 7. The comparison between the results of this article and that for the network involving reuse only obtained by Li et al. [18] is shown in Table 10. It can be seen from Table 10 that the consumption of freshwater can be reduced

Table 7
Limiting data for one production cycle for Example 2

Process	Time/h		Contaminant	$C^{lim,in}/\text{mg}\cdot\text{kg}^{-1}$	$C^{lim,out}/\text{mg}\cdot\text{kg}^{-1}$	M/kg	F^{lim}/t
	Charge	Discharge					
1	0.0–1.0	4.0–5.0	A	0	100	3	30
			B	0	90	2.7	
			C	0	50	1.5	
2	0.0–0.5	4.5–5.0	A	40	150	8.25	75
			B	60	80	1.5	
			C	20	70	3.75	
3	5.0–6.5	5.0–6.5	A	170	170	0	40
			B	120	120	0	
			C	100	100	0	
4	2.0–2.5	6.5–7.0	A	110	210	3	30
			B	135	200	1.95	
			C	60	120	1.8	
5	7.0–8.5	7.0–8.5	A	170	170	0	40
			B	120	120	0	
			C	100	100	0	

Table 8
Order of the CPD values for Example 2

D_j	D_1	D_2	D_4	D_3	D_5
CPD (D_j)	0	1.11	3.30	4.34	4.34
Order	1	2	3	4	5

by 62.5% by introducing a regeneration unit, whose inlet concentrations are (150.00, 82.48, 70.58) $\text{mg}\cdot\text{kg}^{-1}$ and outlet concentrations are (40, 60, 20) $\text{mg}\cdot\text{kg}^{-1}$. The above design procedure shows that the proposed method is very simple.

7. Conclusions

This article presents a heuristic method for the design of batch water-using networks of multiple contaminants with regeneration unit. For the design of a water-using network operated in a single batch, time is taken as the primary factor and the concentration potentials as the secondary one. The network involving reuse only is first designed by dividing the whole network into the subnetwork before regeneration and that after regeneration. Then, the flow rate and concentrations of regenerated stream are estimated. Finally, the network involving regeneration reuse can be obtained by adding the regenerated stream into the original network and designing the obtained network with the method for the network involving reuse only. For the design of a water-using network operated in a repeated mode, the design procedure is similar to that for the continuous network, besides designing the storage tanks with the rules proposed. The regeneration unit operated in continuous mode and it can be modeled either as fixed regenerated concentration model or as fixed removal ratio model. With the proposed method, the water-using network corresponding

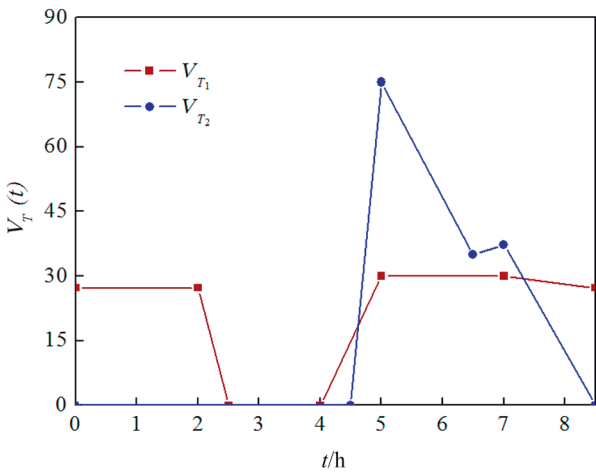


Fig. 6. Storage profile of T_1 and T_2 for Example 2.

to the minimum freshwater consumption can be obtained. It is shown that the method is simple, effective and has clear engineering meaning. It should be indicated that the optimal solutions cannot be guaranteed in this article. They can be used as the initial structures for mathematical programming methods.

Nomenclature

- C concentration of contaminant, $\text{mg}\cdot\text{kg}^{-1}$
- CPD concentration potential of demand
- CPS concentration potential of source
- D demand stream

Table 9
The final inlet and outlet concentrations of each process for Example 2

Process	$C^{in}/\text{mg}\cdot\text{kg}^{-1}$			$C^{out}/\text{mg}\cdot\text{kg}^{-1}$		
	A	B	C	A	B	C
P_1	0	0	0	100		50
P_2	40	60	20	150		70
P_3	150	80	70	150	B	70
P_4	100	90	50	210		116.01
P_5	150	85.31	71.25	150	80	71.25

The shadowed concentrations are those reaching their limiting values.

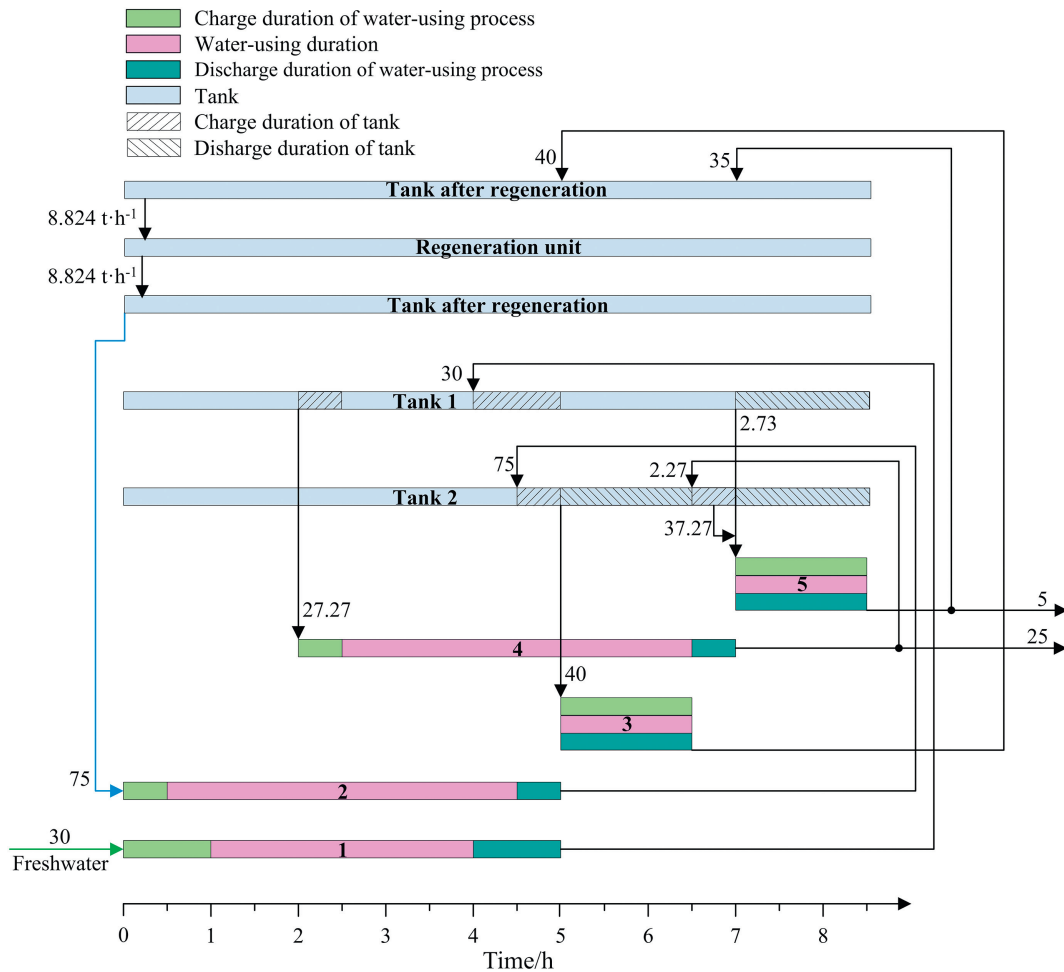


Fig. 7. Final design for Example 2 (where the numbers are the amount of water in t).

F	consumption of stream, kg
FKC	freshwater key contaminant
M	mass load of contaminant, kg
NC	number of contaminants
ND	number of demand streams
NS	number of source streams
R	the maximum quasi-allocation amount
RC	regenerated concentration, $\text{mg} \cdot \text{kg}^{-1}$
RKC	reuse key contaminant
RR	removal ratio, %
S	source stream

Superscripts

in	inlet of a process
lim	limiting value
min	minimum value
out	outlet of a process
rem	removed mass load of a contaminant

Subscripts

$fresh, f$	freshwater
i	a source stream
j	a demand stream
k	a contaminant
reg	regeneration

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Table 10

Comparison of the results for Example 2

Literature	F_f/t	F_{reg}/t	Number of tanks	Interconnection number
Li et al. [18]	83.1	–	3	17
This work	30	75	3	14

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