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# Design of Water Network with Multiple Contaminants and Zero Discharge

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**Abstract** The paper presents a procedure to design water network. First of all, water reuse system, water regeneration reuse system (including regeneration recycle) and wastewater treatment system are designed separately. But the interaction between different parts demands that each part is designed iteratively to optimize the whole water network. Therefore, on the basis of the separated design a water network superstructure including reuse, regeneration and wastewater treatment is established from the system engineering point of view. And a multi-objective adaptive simulated annealing genetic algorithm is adopted to simultaneously integrate the overall water network to balance the economic and environmental effects. The algorithm overcomes the defect of local optimum of simulated annealing (SA), avoids the pre-maturation of genetic algorithm (GA) and finds a set of solutions (pareto front) in acceptable computer time. From the pareto front, a point with minimum fresh water consumption will be extended to zero discharge as our ultimate goal.

**Keywords** water network, wastewater treatment, reuse, regeneration reuse, multi-objective adaptive simulated annealing genetic algorithm, zero discharge

## 1 INTRODUCTION

Water is used widely in the process industries as a raw material. It may be used as a reactant/product in reactors, a mass-separating agent in separation such as absorption, extraction, leaching, and stripping or make-up water in boilers and cooling towers. It is also utilized for equipment cleaning, fire fighting and other miscellaneous consumption. However, in recent years, the increased cost of wastewater treatment to meet environmental requirements and the scarcity of less expensive industrial water prompt process industries to minimize the amount of fresh water utilization and wastewater discharge. There are four general approaches to water minimization: process change, water reuse, regeneration reuse and regeneration recycle[1]. After water usage, wastewater streams are inevitably created. They should be discharged to the environment after treatment or reused/recycled after regeneration. A general approach for wastewater treatment system design is to segregate wastewater streams in the first instance and only mix them if it is appropriate. Usually, water reuse system[2–6], water regeneration reuse system (including regeneration recycle)[7] and wastewater treatment systems[8–10] are designed separately as described in Fig. 1. And a few researchers [11–15] have tried to design the structure in Fig. 2. But usually the economic benefit was regarded as the decisive objective, none has given attention to economic and environmental effects at the same time. However, as our optimal end the solution of the structure of zero discharge[16] in Fig. 3 was never attempted, neither in academic studies nor in practice. Goldblatt, *et al.*[17] discussed the reality of the concept of zero discharge from the practical point of view.

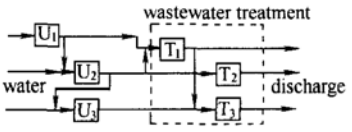

**Figure 1** Conventional design of the water network

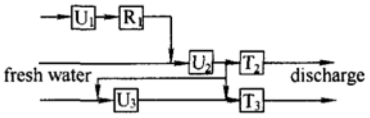

**Figure 2** Integrated design of the water network

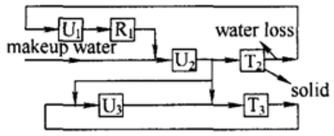

**Figure 3** A zero liquid discharge scheme

There are traditionally two methods used to obtain good designs of water reuse system, regeneration reuse system (including regeneration recycle) and wastewater treatment system: conceptual approach and mathematical programming. As two design methods for water network, conceptual approach and mathematical programming have their own advantages and disadvantages and the whole area is moving toward mathematical programming methods. In

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this paper, water reuse system, regeneration reuse system and wastewater treatment were designed separately. The interaction between different parts was discussed. Then, A multi-objective optimization was adopted to integrate the overall water network. At last, the solutions of the structure of zero discharge were attempted. A combination of pinch technology and mathematical programming was used to design water reuse network. That is to say, the strict model was formulated and the pinch technology was used to obtain good initial points for solutions. For wastewater treatment system design GAMS software package[18] is used. Otherwise, with the increasing concern on environmental protection, multi-objective optimization was adopted to balance the economic and environmental effects in the integration of the overall water network. Recently, evolutionary search algorithms have been shown to be efficient for it. Hereon, a multi-objective adaptive simulated annealing genetic algorithm was adopted to integrate water network.

## 2 PARTIAL DESIGN: WATER REUSE SYSTEM, REGENERATION REUSE SYSTEM AND WASTEWATER TREATMENT SYSTEM

### 2.1 Water reuse system

Given a set of water-using processes, it is desired to determine a network of interconnections of water streams among the processes so that the overall fresh water consumption or annualized cost is minimized while the processes receive water of adequate quality. The above is the description of the design of water reuse system. Besides, the load of contaminants is fixed and the inlet and outlet concentrations of each pollutant are limited according to corrosion, fouling and maximum solubility, *etc.* The model of water reuse system is shown in Fig. 4 and gives the following formulas.

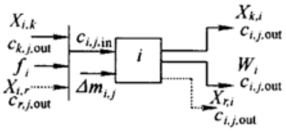

**Figure 4** **The model of water reuse system**

$$\min \sum_i f_i \tag{1}$$

s.t.

$$\sum_{k \neq i} (c_{i,j,\text{in}}^{\max} - c_{k,j,\text{out}}) X_{i,k} + f_i c_{i,j,\text{in}}^{\max} \geqslant 0 \tag{2}$$

$$\sum_{k \neq i} (c_{i,j,\text{out}} - c_{k,j,\text{out}}) X_{i,k} + f_i c_{i,j,\text{out}} = \Delta m_{i,j} \tag{3}$$

$$f_i + \sum_{k \neq i} X_{i,k} - W_i - \sum_{k \neq i} X_{k,i} = 0 \tag{4}$$

$$c_{i,j,\text{out}} \leqslant c_{i,j,\text{out}}^{\max} \tag{5}$$

$$X_{i,k} - V Y_{i,k} \leqslant 0$$

$$X_{k,i} - V Y_{k,i} \leqslant 0$$

$$Y_{i,k} + Y_{k,i} \leqslant 1 \quad k \neq i, Y_{i,k}, Y_{k,i} \in 0,1 \tag{6}$$

The mixed integer non-linear programming (MINLP) problem is relatively difficult to solve especially for a large scale one, the pinch rules are used to reduce the number of integer variables. The water-using processes are divided into two parts: below the pinch and above the pinch for each contaminant. If the reuse from the uints $i$ to $k$ is satisfied for each contaminant according to pinch rule that there is no fresh water passing through the pinch, $Y_{k,i}$ exists, or else it does not exist.

### 2.2 Regeneration reuse system

The regeneration process is a special case of water-using processes whose performance is specified by two general criteria on the waste content: a minimum outlet concentration or a removal ratio. We assume that the flowrate of water before and after regeneration is the same and the regeneration unit is specified by a removal ratio. So in Fig. 4 $X_{i,\text{r}}$ and $X_{\text{r},i}$ are added. Also, the balance equations are

$$\sum_i X_{i,\text{r}} = \sum_i X_{\text{r},i} \tag{7}$$

$$(1 - R_{\text{r},j}) \sum_i X_{\text{r},i} c_{i,j,\text{out}} = \sum_i X_{\text{r},i} c_{\text{r},j,\text{out}} \tag{8}$$

### 2.3 Wastewater treatment system

Wastewater treatment in the process industries is most often carried out in a central treatment facility. But McLaughlin *et al.*[19] realized that the capital cost of most waste treatment operations is proportional to the total flow of wastewater and that the operating cost for treatment increases with decreasing concentration for the given mass of contaminants. So in distributed wastewater treatment, streams are either treated separately only or partially mixed which reduces the flow rate to be processed when compared with centralized wastewater treatment systems. According to Galan and Grossmann[10], the problem of synthesizing a distributed wastewater network can be stated as follows: Given a set of process liquid streams, of known flow rates, that contain certain pollutants with known concentrations. Given is also a set of technologies for the removal of each pollutant. The goal of this problem is to identify the interconnections of the technologies, and their corresponding flow rates and compositions that will meet the discharge composition regulations for each pollutant at a minimum total cost.

One approach to solve this problem is to create a superstructure for the final network containing all structural features resulting from the individual subnetworks shown in Fig. 5. That superstructure includes splitter (S), mixer (M), treatment unit (T), and their interconnections. Because the streams can be fed to treatment processes in any sequence, the solution of the superstructure model is a mixed integer nonlinear programming problem. In the superstructure, mass balance of mixer and splitter is simple so it has not been listed. Treatment units are specified by removal ratio whose mass balance and constraints are listed in Eqs. (9)—(11). The objective of optimization is to minimize the total cost of all treatment units.

$$\min\sum_{\mathrm{t}}[A_{\mathrm{t}}(f_{\mathrm{t}})^{\beta}+B_{\mathrm{t}}f_{\mathrm{t}}] \tag{9}$$

$$F_{\mathrm{s}}=F_{\mathrm{m}} \tag{10}$$

$$c_{\mathrm{s},j}=\sum_{\mathrm{t}}Y_{\mathrm{m,t}}(1-R_{\mathrm{t},j})c_{\mathrm{m},j} \tag{11}$$

$$\sum_{\mathrm{m}}Y_{\mathrm{m,t}}=1,\quad \sum_{\mathrm{t}}Y_{\mathrm{m,t}}=1 \tag{12}$$

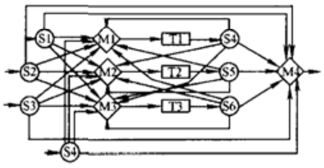

**Figure 5** **The superstructure of wastewater treatment system[10]**

## 3 THE INTEGRATED DESIGN OF WATER NETWORK

In water reuse system design, there might be many water networks that satisfy the fresh water target, but different water reuse network designs will create different treating problems. The use of water can be minimized by reuse. Water can also be regenerated to allow further reuse or recycle. How to select reasonable reuse or regeneration reuse is another problem that should be considered. Although freshwater can be minimized through water reuse and regeneration reuse, the mass load to be removed from the wastewater will not change. Besides, although the interactions between the water reuse system, water regeneration reuse system and wastewater treatment system can be handled with an iterative procedure, these subsystems were still constructed individually. As a result, opportunities of integrating different types of water consumption/treatment units within a unified framework may be overlooked. The overall water network design is necessary. Due to the fact that units in the regeneration system and in the wastewater treatment system are installed essentially for the same purpose, the regeneration units are looked as a special case of wastewater treatment units. In order to balance economic and environmental effects, we expect the water consumption that represents environmental effect and the economic cost are minimized simultaneously. The mathematical model is formulated as the following

$$\min\sum_{i}f_i$$

$$\min\sum_{\mathrm{t}}[A_{\mathrm{t}}(f_{\mathrm{t}})^{\beta}+B_{\mathrm{t}}f_{\mathrm{t}}]+c_{\mathrm{s}}\sum_{i}f_i$$

$$\sum_{k\neq i}(c_{i,j,\mathrm{in}}^{\max}-c_{k,j,\mathrm{out}})X_{i,k}+f_ic_{i,j,\mathrm{in}}^{\max}\geqslant 0$$

$$k\in\{\mathrm{U},\mathrm{T}\},\quad i\in\mathrm{U}$$

$$c_{i,j,\mathrm{out}}\leqslant c_{i,j,\mathrm{out}}^{\max}\quad i\in\mathrm{U}$$

$$\sum_{k\neq i}(c_{i,j,\mathrm{out}}-c_{k,j,\mathrm{out}})X_{i,k}+f_ic_{i,j,\mathrm{out}}=\Delta m_{i,j}$$

$$k\in\{\mathrm{U},\mathrm{T}\},\quad i\in\mathrm{U}$$

$$\sum_{k\neq i}X_{i,k}+f_i=\sum_{k\neq i}X_{k,i}+W_i\quad k\in\{\mathrm{U},\mathrm{T}\},i\in\mathrm{U}$$

$$\sum_{k\neq\mathrm{t}}X_{\mathrm{t},k}=\sum_{k\neq\mathrm{t}}X_{k,\mathrm{t}}+W_{\mathrm{t}}\quad \mathrm{t}\in\mathrm{T},k\in\{\mathrm{U},\mathrm{T}\}$$

$$(1-R_{\mathrm{t},j})\left(\sum_{k\neq\mathrm{t}}X_{\mathrm{t},k}c_{k,j,\mathrm{out}}\right)=\left(\sum_{k\neq\mathrm{t}}X_{k,\mathrm{t}}+W_{\mathrm{t}}\right)c_{\mathrm{t},j,\mathrm{out}}$$

$$\mathrm{t}\in\mathrm{T},k\in\{\mathrm{U},\mathrm{T}\}$$

$$\sum_{k}W_kc_{k,j,\mathrm{out}}\leqslant\sum_{k}W_kc_{\mathrm{l},j}\quad k\in\{\mathrm{U},\mathrm{T}\}$$

A multi-objective adaptive simulated annealing genetic algorithm (MOASAGA) is used to tradeoff between economic and environmental benefits. The combined algorithm overcomes the defect of local optimum of simulated annealing (SA), and avoids the prematuration of genetic algorithm (GA). In order to guarantee the capability of the algorithm, there are more improving measures. (1) Simulated annealing is selected as the main body of the combined algorithm, and the genetic algorithm is embed in its inner framework. Because simulated annealing is simple in form, flexible in use, and robust, genetic algorithm is good at global optimization. (2) The strategy of determining the crossover and mutation probability adaptively keeps the diversity of population and the balance of selection pressure, since the genetic algorithm has great effect on the capability of the hybrid algorithm. (3) The strategy of adjusting the step adaptively is helpful to improve the calculation efficiency of the hybrid algorithm. The flow chart of MOASAGA is shown in Fig. 6. At last, a set of solutions (pareto front) can be acquired and the optimum is selected from the pareto

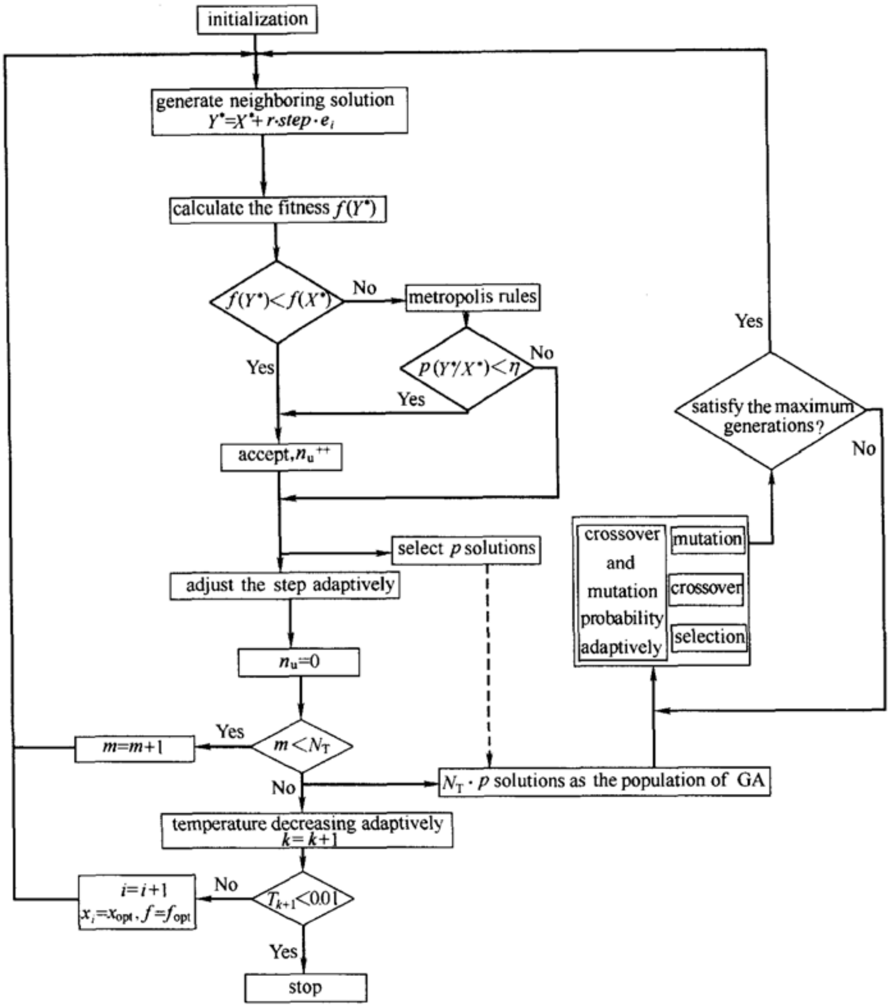

Figure 6 The flowchart of MOASAGA

front according to some requirements. The results of testing functions in the form of non-linear programming (NLP) and mixed integer non-linear programming (MINLP) indicate the hybrid algorithm can deal with the optimization with non-linear constraints, and MINLP can be solved through the suitable management of the integer variables. A case study is used to illustrate its efficiency in the following.

## 4 ZERO DISCHARGE

Zero discharge is the ultimate goal of water reuse. It means no wastewater discharge to the environment. This is the aim set by process plants that consider that treatment and reuse of total plant effluent is more cost-effective than to treat it for discharge. Zero discharge will eliminate the reliance of a process plant on raw water. And from the results of multi-objective optimization, it is possible to realize zero discharge by increasing the regeneration cost. But if the fresh water is expensive which makes cost decrease and there is excess benefit from zero discharge, zero discharge is satisfactory. Zero discharge also means that the overall water network is taken as a closed circuit. So when we solve the structure of the zero discharge system, many recycle streams must be cut. The selection of interception position must refer to the results of multi-objective optimization and their network structure sensitivity analysis.

## 5 CASE STUDY

There are five water using units in the case study[13] since similar water using operations have been combined. The specified conditions are shown in Table 1. The removal ratios for wastewater treating units and regeneration units are specified in Table 2. Treatment process 1(T1) is a steam stripper which only removes $H_2S$. Treatment process 2(T2) is biological treatment and affects hydrocarbon, suspended solids and $H_2S$. Treatment process 3 (T3) is an API separator which can remove hydrocarbon and suspended solids. The discharge limits for hydrocarbon, $H_2S$ and suspended solids are $20\,mg\cdot L^{-1}$, $5\,mg\cdot L^{-1}$, 100 mg·L$^{-1}$, respectively. The capital and operating cost data for treatment processes are shown in Table 3. The annual rate of return rate is 10% and the plant is assumed to operate for 8600 h per year. In addition, it is assumed that the raw water costs 0.20\$·t$^{-1}$.

**Table 1** The specified conditions of water using units for the case study

| Operation | Flow rate t·h$^{-1}$ | Contaminant | $c_{in}$ mg·L$^{-1}$ | $c_{out}$ mg·L$^{-1}$ |
|---|---|---|---|---|
| steam stripping | 50 | H.C | 0 | 15 |
| | | $H_2S$ | 0 | 400 |
| | | S.S | 0 | 35 |
| hydro-desulphurization I | 34 | H.C | 20 | 120 |
| | | $H_2S$ | 300 | 12500 |
| | | S.S | 45 | 180 |
| desalter | 56 | H.C | 120 | 220 |
| | | $H_2S$ | 20 | 45 |
| | | S.S | 200 | 9500 |
| ejector steam for vacuum column | 8 | H.C | 0 | 20 |
| | | $H_2S$ | 0 | 60 |
| | | S.S | 0 | 20 |
| hydro-desulphurization Ⅱ | 8 | H.C | 50 | 150 |
| | | $H_2S$ | 400 | 8000 |
| | | S.S | 60 | 120 |

**Table 2** Treatment units data for the case study

| Treatment process | Removal ratio, % | | |
|---|---|---|---|
| | H.C | $H_2S$ | S.S |
| T1 | 0 | 99.9 | 0 |
| T2 | 70 | 90 | 98 |
| T3 | 95 | 0 | 50 |

**Table 3** Economic data for treatment processes in case study

| Treatment process | Capital cost \$ | Operating cost \$·h$^{-1}$ |
|---|---|---|
| T1 | $16.800 \times f^{0.7}$ | $1.0 \times f$ |
| T2 | $12.600 \times f^{0.7}$ | $0.0067 \times f$ |
| T3 | $4.800 \times f^{0.7}$ | 0 |

If every water using unit is supplied with fresh water without any reuse opportunity, the fresh water requirement is 153.6 t·h$^{-1}$ and the total cost is 1710000 \$·a$^{-1}$. After implementing the water reuse rules and optimizing with GAMS, the fresh water consumption decreases to 111.8 t·h$^{-1}$. That is to say, the reuse of process 1 to 3 ($X_{3,1}$), process 1 to 2 ($X_{2,1}$), process 1 to 5 ($X_{5,1}$), process 4 to 3 ($X_{3,4}$), process 3 to 2 ($X_{2,3}$), process 3 to 5 ($X_{5,3}$)exist. Meanwhile, 111.8 t·h$^{-1}$ wastewater is generated and split into four streams. The wastewater treatment units are used as a sequence of T3, T1, T2 through optimization, which makes the treated wastewater capacity and the treatment cost minimized. The reuse and treatment structure of water network is shown in Fig. 7 and the total cost is 700000 \$·a$^{-1}$. Furthermore, the superstructure of five water using units and three wastewater treating units is built and optimized using the multi-objective adaptive simulated annealing genetic algorithm. A set of solutions (pareto front) acquired is shown in Fig. 8. According to the pareto front, the results of multi-objective optimization indicate that T1 can be seen as regeneration unit. The integrated water network structure is selected according to the weighting factor assignment of the fresh water consumption and the total cost. If the weithting factor of fresh water is larger, that is to say, the fresh water consumption is less because of the water resource scarcity. The minimum fresh water consumption acquired in this paper is 58 t·h$^{-1}$ whose total cost is 659000 \$·a$^{-1}$ shown in Fig. 9, which is less than the result of 677000 \$·a$^{-1}$ in Ref. [13]. Finally, many advanced treatment units can be used to remove residual contaminants with low concentration. For example, low concentration $H_2S$ can be easily removed by oxidation sediment, carbon adsorption can be used to eliminate the influence of H.C to the reverse osmosis. The effluent of reverse osmosis can attain the water with boiler quality, which is a possible approach for zero liquid discharge.

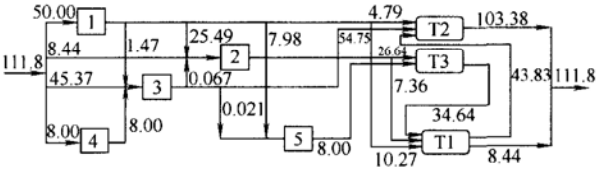

**Figure 7** The design result of water network separately for case study (t·h$^{-1}$)

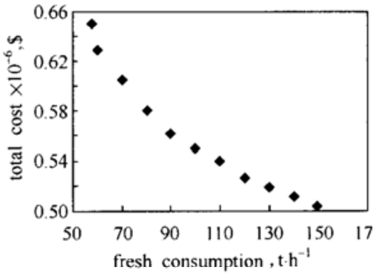

**Figure 8** The pareto front of case study

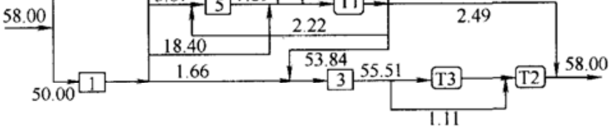

**Figure 9** The integrated water network for case study (t·h$^{-1}$)

## 6 CONCLUSIONS

(1) Fresh water consumption and wastewater discharge can be reduced greatly through reuse, regeneration reuse and regeneration recycle, which can not

only save fresh water but also satisfy process industry water demand.

(2) The economic and environmental performances are considered simultaneously during water network design, which is imperative and reasonable for the requirement of sustainable development strategy. In this paper, not only the model of water network is built but also a suitable algorithm is used to solve it.

(3) Zero liquid discharge is possible after the optimal integrated design of water network.

## NOMENCLATURE

| | |
|---|---|
| $A_t$ | coefficient of capital construction cost |
| $B_t$ | coefficient of operating cost |
| $c$ | concentration of contaminant, $mg \cdot L^{-1}$ |
| $e$ | unit vector |
| $F$ | flow rate, $t \cdot h^{-1}$ |
| $f$ | water flow rate, $t \cdot h^{-1}$ |
| $f()$ | fitness function |
| $i$ | serial number of partial variable in solution vector |
| $k$ | temperature falling times |
| M | mixer |
| $m$ | step adjusted times |
| $N_T$ | temperature adjusted period |
| $n_u, n_u^{++}$ | the number of solutions generated by SA |
| $p$ | the number of solutions selected from the results of SA |
| $R$ | regeneration process |
| $R_{t,j}$, $R_{r,j}$ | removal ratio |
| $r$ | random number between [−11] |
| S | splitter |
| T | treatment process |
| $T_k$ or $T_{k+1}$ | annealing temperature |
| U | water using process |
| $V$ | the constant whose value is greater than the maximum flow rate in water utilization network |
| $W$ | wastewater flow rate, $t \cdot h^{-1}$ |
| $X$ | reuse flow rate, $t \cdot h^{-1}$ |
| $X^*$ | initial solution |
| $x$ | decision variable |
| $x_{opt}$ | optimum of decision variable |
| $Y$ | binary variable, the connection from $i$ to $k$ exists, $Y$ equals 1, or else it equals 0 |
| $Y^*$ | neighboring solution |
| $\Delta m$ | contanminant load, $kg \cdot h^{-1}$ |
| $\alpha$ | temperature falling coefficient |
| $\beta$ | capital cost exponent |
| $\eta$ | random probability |

### Subscripts

| | |
|---|---|
| $i$ | water using unit |
| in | inlet |
| $j$ | contaminant |
| l | limit |
| $k$ | water using units and treating units |
| m | mixer |
| out | outlet |
| opt | optimum |
| r | regeneration unit |
| s | splitter |
| t | treatment unit |

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