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Water Allocation Network Synthesis Involving Reliability Analysis

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Water supplies in some countries are a severe problem. Where this is so, legislation to reduce fresh water consumption has been strengthened over the years. The purpose of water allocation network (WAN) synthesis is to reduce freshwater consumption and wastewater discharge, while maintaining network reliability, safety and maintenance cost. The structure of WAN has a significant impact on reliability issues. In this paper reliability analysis is integrated into the WAN synthesis problem. In order to obtain a WAN that is reliable and consumes the minimum freshwater, an example presented to illustrate the application of the proposed method demonstrates the method is effective.

1. Introduction

Water is a key element for the normal functioning of industry and society. A large number of studies about water allocation network (WAN) synthesis to reduce freshwater consumption and wastewater discharge in chemical industry have been reported over the past two decades.

Many methods have been presented to study the water allocation problem. Takama et al. (1980) first described a water allocation network (WAN) in a petroleum refinery with a superstructure of all reuse possibilities and proposed a mathematical programming as a method to solve the problem. Wang and Smith (1994) proposed the water pinch method with the creative concepts of water pinch and limiting water profile. The method soon became a graphical method that is now widely applied to chemical industry. The graphical methods are difficult to deal with large-scale water allocation problem and multi-contaminant problem. Doyle and Smith (1997) presented linear programming (LP) and non-linear programming (NLP) methods to minimize freshwater consumption of water networks with multi-contaminant. Alva-Argaez et al. (1999) optimized water reduction problems by combining water-pinch analysis techniques with mathematical programming tools. Gunaratnam et al. (2005) also applied non-linear mathematical programming (NLP) methods to minimizing freshwater consumption of water using networks. For finding the global optimum, Savelski and Bagajewicz (2000) developed necessary conditions for the optimal water allocation problem. Liu et al. (2009) proposed a new concept of concentration potential to deal with multiple contaminants problem. This new method has achieved some progress in recent three years.

Researches on reliability analysis in the chemical industry began in1960s, but make a little progress in many years. In recent years, scientists focus on this topic again. Goel et al (2002) proposed an optimization framework by combining the reliability optimization with process synthesis challenges for large integrated chemical process systems. Sikos and Klemeš (2010) used comprehensive up-to-date commercial software tools to manage reliability problem of heat exchanger network. Reliability analysis of water allocation networks is relatively new. The reliability of a network depends on the reliability of individual units and the complexity of the network structure. This paper integrates reliability analysis into the WAN synthesis problem and focus on simplify the structure of the water allocation network before improving the reliability of a single unit. A WAN which satisfies certain reliability criterion while also consuming the minimum amount of freshwater is the goal.

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2. Problem statement

The problem of water allocation network synthesis involving reliability analysis can be briefly stated as follows. Given a set of water-using units $i \in P$ in which some contaminants $k \in K$ with fixed mass loads $M_{i,k}$ are required to be removed and the maximum permissible inlet concentrations $c_{i,k}^{in,\max}$ and the maximum outlet concentrations $c_{i,k}^{\text{out,max}}$ for each unit are specified; only freshwater is supplied as the external water source; reliability of each water-using unit R_i is specified and the reliability of the network only relates to the reliability of the units and the structure of the network. There is neither water loss nor reactions among contaminants or phase change. This problem targets the optimal network configuration which determines the minimum freshwater consumption and the resultant network structure that satisfies the reliability issues.

3. Mathematical model

3.1 Superstructure

Figure 1 describes the water utilisation network superstructure model of a single process. This superstructure model includes all possibilities of water reuse.

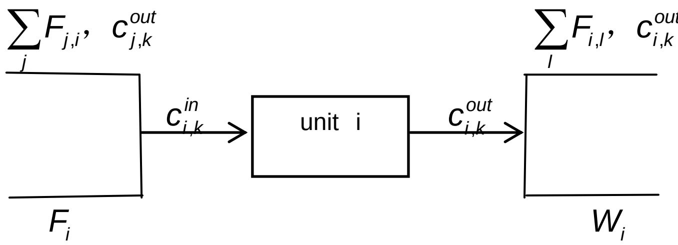

Figure 1: Water utilization network superstructure model of a single operation unit

3.2 Nonlinear programming model

A non-linear programming mathematical model is established to determine the minimum freshwater requirement and the initial network structure.

Objective function

$$F = \min \sum_i F_i \tag{1}$$

Mass balance of contaminants of the inlet mixing point of unit i:

$$\sum_{\substack{i,j \in P \\ i \neq j}} (F_{j,i} c_{j,k}^{out}) = (F_i + \sum_{\substack{i,j \in P \\ i \neq j}} F_{j,i}) c_{i,k}^{in} \tag{2}$$

Mass balance of contaminants of the out splitting point of unit i:

$$(F_i + \sum_{\substack{i,j \in P \\ i \neq j}} F_{j,i}) c_{i,k}^{in} + M_{i,k} = (W_i + \sum_{\substack{i,j \in P \\ i \neq j}} F_{i,l}) c_{i,k}^{out} \tag{3}$$

Water balance of unit i:

$$F_i + \sum_{\substack{i \in P \\ i \neq j}} F_{j,i} = W_i + \sum_{\substack{l \in P \\ i \neq l}} F_{i,l} \tag{4}$$

Limit of inlet concentrations of contaminant of unit i:

$$0 \leq c_{i,k}^{in} \leq c_{i,k}^{in,\max} \tag{5}$$

Limit of outlet concentrations of contaminant of unit i:

$$0 \leq c_{i,k}^{out} \leq c_{i,k}^{out,\max} \tag{6}$$

Nonnegative restriction of flow:

$$0 \le F_i, 0 \le F_{j,i} \tag{7}$$

4. Reliability analysis

Reliability issues in water allocation network are worth considering ensuring safety in production. The problems are how to calculate the reliability of a water network already that already exists and how to improve the reliability of a water network that can't meet the process specification. After obtaining the minimum freshwater consumption target and the initial network structure, the reliability of the initial WAN can be evaluated. Subsystems of the network are recognized from the incidence matrix based on the initial network and the overall reliability of WAN is evaluated in terms of the network subsystems and then for the whole system. For the subsystem whose reliability fails to meet the process specification, simplification of the network subsystem structure is imperative.

Reliability of subsystem:

$$R_{ss} = \prod_i R_i \tag{8}$$

Reliability of the whole system:

$$R_s = \min R_{ss} \tag{9}$$

Network simplification is done by replacing water-use streams with fresh water streams based on an agreed criterion. Replacing water-reuse stream in a subsystem is desirable provided the subsystem reliability is improved to compensate for the extra cost associated with more fresh water. Re-optimizing the initial WAN after removing the specified stream, enables a new minimum fresh water consumption value to be identified. Further, removing a different stream generates another simplified WAN which then has to be evaluated and compared to the previous one.

To find the optimum WAN easier and avoid calculating all the options one by one, two rules should be observed. First is feasible rule, which means stream removal is feasible only if it can improve the system reliability to the required amount. Second is efficiency rule. That is to say if there are two options can increase the system reliability to the same level, choose the option of the removal stream with a higher concentration and lower flow rate.

5. Example from literature

The example, taken from Wang et al (2003), is a multi-contaminant system with seven water-using units. The limiting data is given in Table1.

Table 1: Limiting data of example

Water-using unit	$C_{i,k}^{in,\max}$ (ppm)			$C_{i,k}^{\text{out},\max}$ (ppm)			$F_i^{\max}$ (t/h)
	A	B	C	A	B	C	
1	0	0	0	50	100	50	25
2	0	0	0	100	300	600	70
3	20	50	50	150	400	800	35
4	50	110	200	600	450	700	40
5	20	100	200	500	650	400	8
6	500	300	600	1100	3500	2500	50
7	150	700	800	900	4500	3000	30

The mathematical model described in section 3 was used to solve the example problem. The minimum freshwater consumption of the system is 140.93 ($t \cdot h^{-1}$). Table 2 shows the actual data of the example. And the initial water network is as Figure 2.

Table 2: Actual data of example

Water-using unit	$C_{i,k}^{in}$ (ppm)			$C_{i,k}^{out}$ (ppm)			F_i (t/h)
	A	B	C	A	B	C	
1	0	0	0	50	100	50	25
2	0	0	0	100	300	600	70
3	13.71	27.42	13.71	150	394.36	800	24.23
4	41.94	110	172.58	591.94	450	672.58	16.90
5	20	40	100	500	590	220	4.80
6	300	600	150	700	3500	2500	0
7	150	373.22	709.97	900	4173.22	2902.97	0

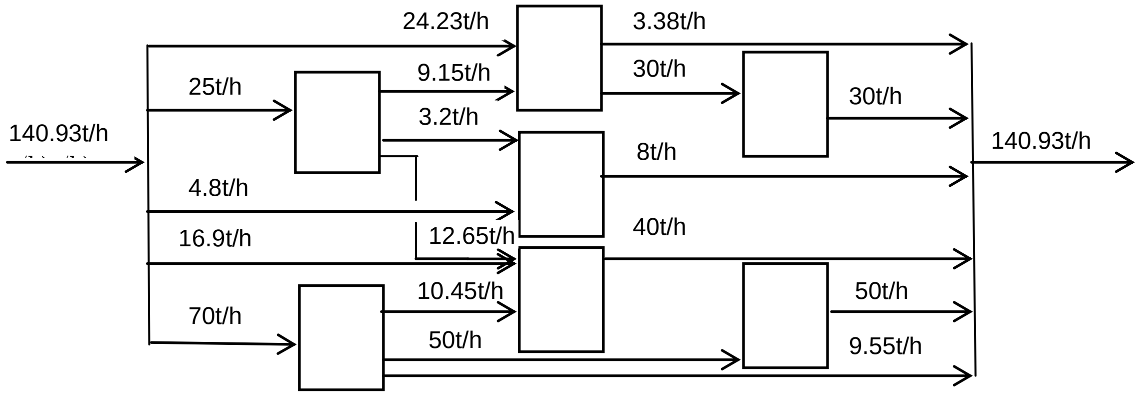

Figure 2: The initial water network of the example

The incidence matrix of the initial network is as follows:

$$
\begin{array}{c}
\begin{array}{cccccccc} & 1 & 2 & 3 & 4 & 5 & 6 & 7 \end{array} \\
\left[\begin{array}{cccccccc}
1 & 0 & 1 & 1 & 1 & 0 & 0 & \\
2 & 0 & 1 & 0 & 1 & 0 & 1 & 0 \\
3 & 1 & 0 & 1 & 0 & 0 & 0 & 1 \\
4 & 1 & 1 & 0 & 1 & 0 & 0 & 0 \\
5 & 1 & 0 & 0 & 0 & 1 & 0 & 0 \\
6 & 0 & 1 & 0 & 0 & 0 & 1 & 0 \\
7 & 0 & 0 & 1 & 0 & 0 & 0 & 1
\end{array}\right]
\end{array}
$$

Figure 3: Incidence matrix of the initial water using network

In the incidence matrix (Fig.3), numbers 1~7 in the first line and row represent water-using units; elements 1, 0 denote connections of the units or not. Here, diagonal element means connection to water-using unit within it and it is commanded to be 1. Subsystems of the network are then be recognized from the incidence matrix based on the initial network. It is obvious from Fig.4, that there is only one subsystem which contains all the seven water-using units. The reliability of each unit is assumed to be 0.98, which means that the failure rate is 0.02 and reliability asked for the system is 0.90. For this case,

$$R_s = R_{ss} = \prod_i R_i = 0.98^7 = 0.87 < 0.90$$

$$\begin{array}{c|ccccccc} & 1 & 2 & 3 & 4 & 5 & 6 & 7 \\ \hline 1 & 1 & 0 & 1 & 1 & 1 & 0 & 0 \\ 2 & 0 & 1 & 0 & 1 & 0 & 1 & 0 \\ 3 & 1 & 0 & 1 & 0 & 0 & 0 & 1 \\ 4 & 1 & 1 & 0 & 1 & 0 & 0 & 0 \\ 5 & 1 & 0 & 0 & 0 & 1 & 0 & 0 \\ 6 & 0 & 1 & 0 & 0 & 0 & 1 & 0 \\ 7 & 0 & 0 & 1 & 0 & 0 & 0 & 1 \end{array}$$

Figure 4 Procedure of recognizing subsystems of the initial network

The reliability of the system fails to meet the process specification, therefore, if improving reliability of single unit is not considered, structure simplification of the system is imperative. Here, the reliability can be improved by removing any water-reuse stream in the system. Removing water-reuse streams in the system is theoretically allowed but such action probably adds freshwater consumption.

From the two rules in section 4, the removal of S_{3-7}, S_{2-6} and S_{1-5} are infeasible as for the improvement of system reliability. For $F_{1-4} > F_{2-4}$, the removal of S_{1-4} is better than the removal of S_{2-4} in terms of the additional fresh water. There are two options left only, Compare fresh water consumption in new network structure and obtain the optimum.

Results of minimizing freshwater consumption and reliability improvement of all possible options are shown in Table 3. The best choice is the removal of S_{1-3} which meets the reliability specification 0.90 with the minimum freshwater consumption 143.41 t/h. The final structure of the water network corresponding to the removal of the system is as Figure 5.

For this example, reliability of the water allocation work is improved to an appropriate value (from 0.87 to 0.9) with only a 1.75 % increase in freshwater consumption (from140.93 t/h to 143.41 t/h) . Improving the reliability of single unit to improve reliability of the network is not always possible. So this method is effective and could be accepted by industry.

Table3: result of all possible options for improving reliability of the system

	Removal S_{1-4}	Removal S_{2-4}	Removal S_{1-3}	Removal S_{1-5}	Removal S_{3-7}	Removal S_{2-6}
Freshwater consumption t/h	147.47	149.05	143.41	141.68	163.55	179.50
System Reliability	0.92	0.90	0.90	0.89	0.89	0.89

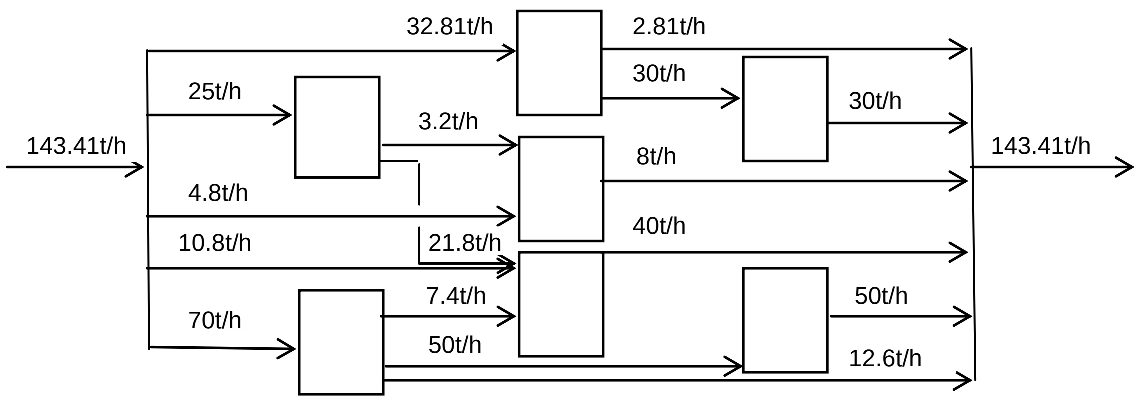

Figure5: The final network of the example

6. Conclusions

The aim of this work was to deal with reliability analysis problems in water allocation network. A method was proposed to calculate the reliability of a water network already existed and improve the reliability of the network that can't meet the process specification. For improving reliability of single unit is always difficult to realize, this paper improves system reliability by simplifying the structure of the network which means replacing some re-use stream with fresh water. Theoretically, any water reuse stream can be removal to improve the reliability of the network. While, for water allocation network, freshwater consumption is always the target. So the final water allocation network should consume the minimum freshwater with the appropriate reliability. To calculate easily, two removal rules should be observed: feasible rule and efficiency rule. The example in this paper shows this procedure in detail, reliability improved to appropriate value with 1.75% increasing of freshwater consumption. This result means this method is effective and could be accepted by industry.

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