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Inter-plant Water Integration with Considerations of Water Supply Constraint and Differential Water Price

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The recent increase in awareness of industrial ecology has inspired research in inter-plant water integration. Industrial water conservation and wastewater reduction are becoming increasingly important for sustainable water resource development in industrial parks. Water supply and pricing structures provide incentives to increase water recovery ratio. This work proposes a superstructural-based mathematical optimization method for total water networks with constrained freshwater supply. This work first explores the implications of differential price, minimum freshwater flowrate, and the number of regeneration units for different constrained water supplies. Considering minimum water-using cost as the optimization objective, the minimum freshwater flowrate and its corresponding total water network structural are determined.

1. Introduction

Water resource scarcity and increasing water prices in the process industries have spurred research efforts focusing on the reduction of freshwater consumption and treatment costs through water reuse, recycling, and regeneration. These problems have been addressed as part of a synthesis of intra-plant and inter-plant water integration from a process system engineering perspective. Many systematic design methods for water conservation based on process integration methodologies have been emerged. Such methodologies reported for intra-plant water networks have been summarized in the review articles by Bagajewicz (2000) for fixed flow problems, Foo (2009) for fixed flow rate problems, as well as the literature annotations by Jeżowski (2010).

The recent increase in awareness of industrial ecology has inspired research in inter-plant water integration (IPWI). Olesen and Polley (1996) first addressed practical considerations in IPWI by analyzing the influence of geographical location and piping costs using the pinch-based load table technique. Two different schemes of IPWI is proposed, i.e., unassisted Integration (Chew et al., 2010a) and assisted integration (Chew et al., 2010b). Rubio-Castro et al. (2013) presented a new global optimization method for IPWI problems based on properties and formulated a MINLP model that involves all possible options of interest. Tan et al. (2011) developed a fuzzy bi-level programming model to determine optimal inter-plant water integration networks in eco-industrial parks. Lee et al. (2013) presented a mathematical model for the synthesis of water networks involving mixed batch and continuous units. Chen et al. (2010) proposed IPWI scheme with central and decentralized water mains. In addition, Chew et al. (2009) employed a game-based approach to analyse the interaction of participating companies in an eco-industrial park. Sueviriyapan et al. (2014) develop a generic model-based synthesis process for a water/wastewater treatment network design problem to identify the best wastewater treatment processes with a minimum total annualized cost. Pintarič et al. (2014) performed water networks syntheses based on MINLP model by using various economic objectives, i.e. total annual cost, the net present value, and the annual profit.

The techniques aforementioned may be used to find the minimum freshwater consumption for IPWI problems. However, the synthesis of water networks is a complex task, as there are many parameters that

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influence water reuse/recycle problems. These include the total benefit/cost, constrained freshwater supply, and water price. Jia et al. (2010) proposed a mathematical optimization model for total water networks with constrained water supply and differential water pricing. The aim of this work is to explore the relationships between differential price, minimum freshwater flowrate, freshwater supply, and the number of regeneration units.

2. Methodology

2.1 Problem statement and superstructural models

Given a total water network, it consists of a freshwater supplier, a set *I* of water-using plants, a set *T* of wastewater treatment plants, and a water regeneration plant with *R* water regeneration units. Assume that some basic data are known, including the limiting flowrate, the limiting inlet and outlet concentrations, and the types of contaminant. Additionally, all cost elements are known, such as regeneration water price, regeneration cost, the restricted water flowrate, and freshwater price.

The superstructures for water-using plant, water regeneration plant, and wastewater plant are shown as Figure 1. In Figure 1(a), there are three water inlet streams: the freshwater or available water, the water stream from a regeneration unit with low concentrate, and the reuse water from other water-using plants. These water streams mix in a mixing unit and then enter the water-using plant. During the process, water as a mass separating medium aims to remove the contaminant load in the water-using plant. The outlet streams are divided into three sub-streams by a splitter. These sub-streams enter another water-using plant, the regeneration plant, and the wastewater plants. The mass balance of the mixer is shown in Eq(1) and the constraints of the mixer are shown in Eq(2) – Eq(5). The mass balance of contaminant unit i is shown in Eq(6) and the constraints are shown in Eq(7). The mass balance of the separator for water-using plants are given as shown in Eq(9) – Eq(11).

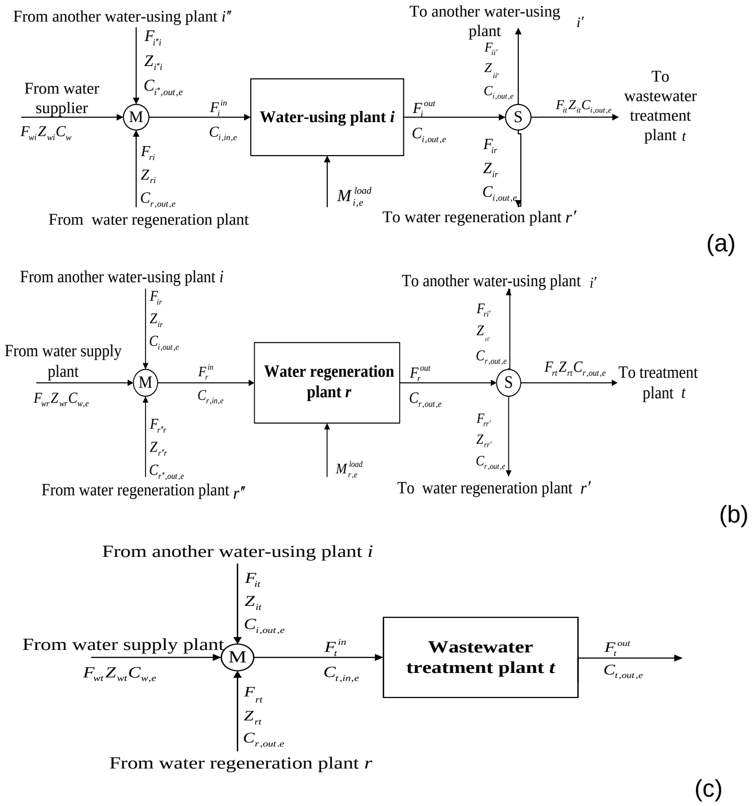

Figure 1 The superstructure for (a) water-using plants; (b) regeneration plants; (c) wastewater treatment plants (M: mixer; S: separator)

Mass balance of the mixer:

$$F_i^{in} = \sum_{\forall i'' \in I} F_{i''i} + \sum_{\forall w \in W} F_{wi} + \sum_{\forall r \in I} F_{ri}, \forall i \in I \qquad (1)$$

$$F_i^{in}C_{i,in,e} = \sum_{\forall i^" \in I} F_{i^"i}C_{i^",out,e} + \sum_{\forall w \in W} F_{wi}C_{w,e} + \sum_{\forall r \in I} F_{ri}C_{r,out,e}, \forall i \in I \tag{2}$$

$$\underline{F_{i^"i}}Z_{i^"i} \le F_{i^"i} \le \overline{F_{i^"i}}Z_{i^"i}, \forall i, i^" \in I \tag{3}$$

$$\underline{F_{wi}}Z_{wi} \le F_{wi} \le \overline{F_{wi}}Z_{wi}, \forall i \in I, \forall w \in W \tag{4}$$

$$\underline{F_{ri}}Z_{ri} \le F_{ri} \le \overline{F_{ri}}Z_{ri}, \forall i \in I, r \in R \tag{5}$$

Where F_i^{in} is the outlet flowrate of the mixer supplied for water-using plant i, $F_{i"i,}$ is the flowrate from water-using plant $i^"$ to plant i. F_{wi} and F_{ri} present the flowrate from freshwater and regeneration unit, respectively. $C_{i,in,e}$ denotes the concentration of contaminant *e* at the inlet of the plant i. $C_{i",out,e}$, $C_{w,e}$ and $C_{r,out,e}$ represent the concentration contaminant *e* from water-using plant $i^"$ ', freshwater and regeneration unit, respectively. $Z_{i"i}$, Z_{wi}, Z_{ri} is a binary variable denoting the existence of the link between the water source and water sink. $\underline{F_{i"i}}$, $\underline{F_{wr}}$, $\underline{F_{ri}}$ is the lower bounds while $\overline{F_{i"i}}$, $\overline{F_{wi}}$, $\overline{F_{ri}}$ is the upper bounds.

Mass balance of contaminant of unit i:

$$M_{i,e}^{load} = F_i^{out}C_{i,out,e} - F_i^{in}C_{i,in,e} \tag{6}$$

$$C_{i,in,e} \le C_{i,in,e}^{\max}; C_{i,out,e} \le C_{i,out,e}^{\max}, \forall i \in R, e \in E \tag{7}$$

Where $M_{i,e}^{load}$ is the removal mass load of contaminant *e* of plant i. F_i^{out} and $C_{i,out,e}$ denote the flowrate and concentration at the outlet of plant i, respectively. Similarly, F_i^{out} and $C_{i,out,e}$ are the flowrate and concentration at the inlet of plant i, respectively. On the other hand, the concentrations at the outlet and inlet of plant i have an upper limit. $C_{i,in,e}^{\max}$ is the maximum concentration for the inlet of plant i, while $C_{i,out,e}^{\max}$ is the limiting concentration for the outlet of plant *i.*

Mass balance of the separator:

$$F_i^{out} = \sum_{\forall i^' \in I} F_{ii^'} + \sum_{\forall r^' \in R} F_{ir^'} + \sum_{\forall t \in T} F_{it}, \forall i, i^' \in I, t \in T, r^' \in R \tag{8}$$

$$\underline{F_{ii^'}}Z_{ii^'} \le F_{ii^'} \le \overline{F_{ii^'}}Z_{ii^'}, \forall i, i^" \in I \tag{9}$$

$$\underline{F_{ir^'}}Z_{ir^'} \le F_{ir^'} \le \overline{F_{ir^'}}Z_{ir^'}, \forall i \in I, \forall r^' \in R \tag{10}$$

$$\underline{F_{it}}Z_{it} \le F_{it} \le \overline{F_{it}}Z_{it}, \forall i \in I, \forall t \in T \tag{11}$$

Where F_i^{out} denotes the outlet flowrate of water-using plant i. $F_{ii^'}$ is the allocated flowrate from plant i to plant $i^'$, while $F_{ir^'}$ and F_{it} present the flowrate allocated to the regeneration unit and wastewater treatment unit, respectively. Similar to the mixer, $Z_{ii^'}$, $Z_{ir^'}$, Z_{it} is a binary variable denoting the existence of the link between the plant i and water sinks, i.e., plant $i^'$, regeneration unit and wastewater treatment unit. $\underline{F_{i"i}}$, $\underline{F_{wr}}$, $\underline{F_{ri}}$ are the lower bounds and $\overline{F_{i"i}}$, $\overline{F_{wi}}$, $\overline{F_{ri}}$ are the upper bounds.

Due to the limited space, the details of all equations for the regeneration and wastewater treatment plants are not listed here.

2.2 Optimization objective function

The objective function of this optimization model seeks to minimize the total cost. The total cost encompasses the costs of freshwater, regeneration, and treatment. The total cost can be written as follows.

$$\min_{x\in\Omega} \text{COST} = \sum_{\forall w\in W}\sum_{\forall i\in I} F_{wi}u_w + \sum_{\forall r\in R}\sum_{\forall i\in I} F_{ri}u_r + \sum_{\forall r\in R} F_r m_r \quad (12)$$

Where COST is the total cost which is the sum of cost of freshwater, reclaimed water and wastewater treatment. In the right-hand side, $\sum_{\forall w\in W}\sum_{\forall i\in I} F_{wi}u_w$ is the total cost of the freshwater consumed by all the plants. F_{wi} is the flowrate freshwater allocated to plant i and u_w is the price of freshwater. $\sum_{\forall r\in R}\sum_{\forall i\in I} F_{ri}u_r$ is the total cost for purchasing the regenerated water. F_{ri} is the allocated flowrate from regeneration unit to plant i and u_r is the price of regenerated water. The last term in the right-hand side is total cost for wastewater treatment. F_r is the flowrate of wastewater to be treated and m_r is the unit cost of wastewater treatment.

3. Case study

The case study analysed in this work is reproduced from Keckler and Allen (1999). The relevant limiting data for water intake and effluent discharge of the plants are given in Table 1. This work assumes that there are three plants in the eco-industrial park marked as M, O, and P. The three water contaminants analysed were total organic carbon (TOC), total suspended solids (TSS), and total dissolved solids (TDS). Here, S represents the freshwater suppliers. The relevant costs are shown in Table 2.

3.1 The total water network under limited water supply

3.1.1. Assuming a supply of freshwater F = 1,000 × 10^3 gal/d

Scenario a: When the freshwater price U is taken as \$ 0.5/10^3 gal, the required minimum consumption of freshwater (F_w) is identified as 1,829 × 10^3 gal/d, i.e., $F_w > F$. In this scenario, the water supply available is given (F = 1,000 × 10^3 gal/d).Therefore, the actual freshwater consumption is equal to F (1,000 × 10^3 gal/d). Additional regeneration flowrate (829 × 10^3 gal/d) is required. The corresponding total water network is shown in Figure 2.

Scenario b: When the freshwater price U is \$ 0.75/10^3 gal, the required minimum consumption of freshwater (F_w) is identified as 529 × 10^3 gal/d. In order to meet the water requirements of the three plants, the flowrate of regeneration water should be increased. Compared with Scenario a, the regeneration flowrate of unit B has increased from 829 × 10^3 gal/d to 1,300 × 10^3 gal/d, an increase of 56.8 %. The corresponding total water network is shown in Figure 3.

Table 1 Water flowrate and quality requirements for three plants and the supplier water quality

Plants	Flowrate (10^3 gal/d)	Inlets limiting concentration (mg/L) (TOC,TSS,TDS)	Outlets limiting concentration(mg/L) (TOC,TSS,TDS)
M	11	(25,500,2500)	(1928,2639,7824)
O	947	(25,25,200)	(484,105,904)
P	1300	(5,100,500)	(8,22,276)
S			(0,1,140)

Table 2 Freshwater and reused water prices, treatment costs, and outlet concentrations

Process	Purchase price (\$/10^3 gal)	Processing costs (\$/10^3 gal)	Outlets concentration after treatment(mg/L) (TOC,TSS,TDS)
A / secondary treatment	0.20	5.50	(20,30,1000)
B / filtration	0.25	0.40	(5,10,500)
H / buffer tank	—	2.00	—
C / reverse osmosis	0.30	6.00	(5,1,10)
S / freshwater	0.75	—	(0,1,140)

3.1.2. Assuming a price of freshwater U fixed at \$ 0.8/103 gal

Scenario c: When the freshwater supply F is fixed at 2,000 × 10^3 gal/d, the required minimum consumption of freshwater F_w is identified as 529 × 10^3 gal/d. The total water network is similar to that in Figure 2.

Scenario d: When the freshwater supply F is fixed at 500 × 10^3 gal/d, the required minimum consumption of freshwater F_w is larger than the supply F. Thus, the minimum consumption of freshwater is chosen as F_w = F = 500 × 10^3 gal/d. In order to meet the needs of three plants, the regeneration units (A/B/C) are all used. The total water network is shown in Figure 4.

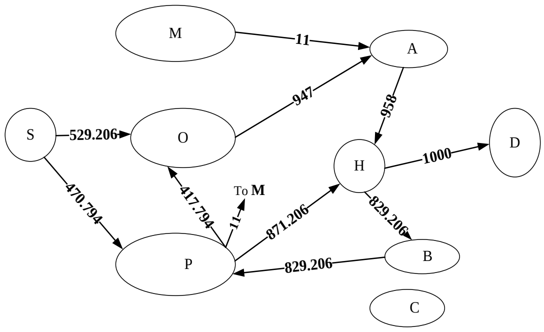

Figure 2 Total water network at U = \$ 0.5/10³ gal and F = 1,000 × 10³ gal/d

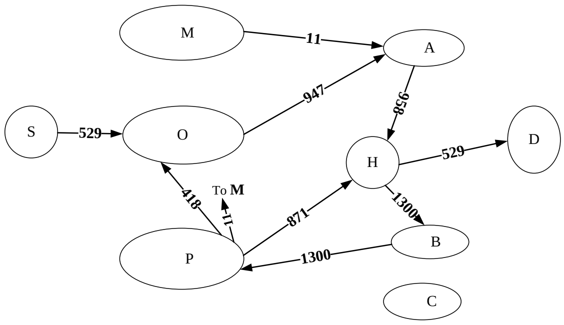

Figure 3 Total water network at U = \$ 0.75/10³ gal and F = 1,000 × 10³ gal/d

3.2 The relationship between *U*, *F*, and *F_w*

Table 3 shows the relevant data describing freshwater price, minimum freshwater flowrate, and regeneration units when freshwater supply F is 2,000 × 10^3 gal/d, 1,000 × 10^3 gal/d, and 500 × 10^3 gal/d, respectively. As shown, for a fixed fresh water supply, its consumption gradually decreases with increasing water price, and more regeneration water units are to be installed. When the constrained water supply is decreased, the corresponding price range of freshwater also decreases and more regeneration water units are used. When the freshwater supply is reduced to 500 × 10^3 gal/d, the regeneration units (A/B/C) are used whichever way prices were presented. When the freshwater price is more than \$ 2.57/10^3 gal, the regeneration units (A/B/C) are all used whichever way the freshwater supply were presented.
When the freshwater supply is less than the minimum freshwater consumption, the final freshwater supply F_w is equal to F. The relationship between the corresponding price range and the minimum freshwater consumption for various freshwater supplies is presented in Table 4.

4. Conclusions

This work could provide technical support for the optimization of inter-plant water integration (IPWI) in industrial parks. In this work, relationships between freshwater price, freshwater supply, minimum freshwater consumption, and the number of wastewater regeneration units were found using mathematical models. When limited boundaries to the freshwater supply were set, the freshwater consumption was found to decrease as freshwater price rises to a certain level. Simultaneously, the number of water regeneration units was found to increase. However, when the freshwater supply was decreased to a particular level, the freshwater price interval was also decreased compared with high water supply scenario, while the number of water regeneration units for this scenario was increased.

Table 3 Relationships between F, U, F_w, and regeneration units

Freshwater supply F (10^3 gal/d)	Freshwater price U (\$/10^3 gal)	Freshwater flowrate F_w (10^3 gal/d)	Regeneration units
	0~0.65	1,829	A
2,000	0.65~2.57	529	A/B
	>2.57	0	A/B/C
	0~0.65	1,000	A/B
1,000	0.65~2.57	529	A/B
	>2.57	0	A/B/C
500	0~2.57	500	A/B/C
	>2.57	0	A/B/C

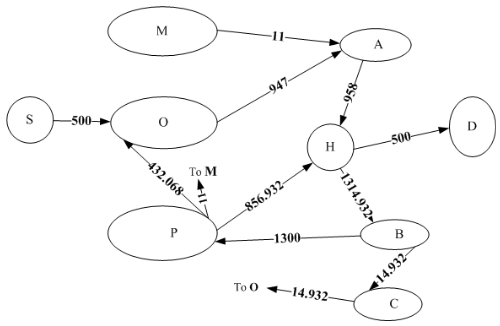

Figure 4 *Total water network at U = \$ 0.8/10^3 gal and F = 500 × 10^3 gal/d*

Table 4 Relationships between F, U, and F_w

Freshwater price U (\$/10^3 gal)	Freshwater supply F (10^3 gal/d)	Freshwater consumption F_w (10^3 gal/d)
0~0.65	F<=1829	F
	F>1829	1829
0.65~2.57	F<=529	F
	F>529	529
>2.57	F>=0	0

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