CHEMICAL ENGINEERING TRANSACTIONS

VOL. 45, 2015

A publication of
AIDIC
The Italian Association
of Chemical Engineering
www.aidic.it/cet

Guest Editors: Petar Sabev Varbanov, Jiří Jaromír Klemeš, Sharifah Rafidah Wan Alwi, Jun Yow Yong, Xia Liu

ISBN 978-88-95608-36-5; **ISSN** 2283-9216

DOI: 10.3303/CET1545201

The Retrofit Design for Water Network with Multiple Contaminants of Industrial Process

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Water is the important resources for process industry. The reduction of water usage decreases the capital cost for process industry. This paper presents a design model of water/wastewater network with multiple contaminants. The main purpose is minimizing the total fixed cost (TFC) and the total annual cost (TAC) of overall water network including annual cost of water usage and water treatment compared between two design models. The first model is retrofit design of water network model by a liner programming (LP) for design with treatment. The second model is simultaneous grassroots design of water/wastewater network with minimum TAC by a mixed-integer non-liner programming (MINLP). According to the main purpose, a non-linear programming (NLP) model is solved for good initial variables for the MINLP in the second model. This model uses data from published work. The result show the grassroots design of water/wastewater network can reduce TAC more than one from the retrofit design. All mathematical models of this work are solved by DICOPT as solver in General Algebraic Modelling System (GAMS).

1. Introduction

Water network is designed for water management in industrial processes and reducing wastewater discharge to environment. The water network helps reduce freshwater consumption cost by generating the optimal flow in water streams to reduce amount of fresh water usage. One of many ways to reduce amount of wastewater is to add treating units at wastewater streams and recycle wastewater streams to the water using processes. The water reuse has been solved by Doyle et al. (1997) with the mass balance calculations under specified outlet concentration of contaminants and linear programming to find a suitable starting point before using non-linear optimization to solve the network. Not only water using parts but also wastewater treating processes need water network for saving water usage and wastewater discharge. Simultaneous design of both water using parts and wastewater treating part reduces more fresh water usage by water/wastewater network (Bagajewicz 2000).The mathematical programming is used for analyzing wastewater discharge with different treatment technologies (Koppol et al., 2003). The key components used as specified contaminants help solve the water network problem with non-linear programming (NLP) model (Savelski et al., 2003). The determination of upper bounds and lower bounds of some specified variables in NLP model becomes important for highly nonlinear problems, water allocations, and the MINLP are used for minimizing water usage by water allocation (Faria et al., 2008). The step model with MILP and MINLP model is used to design the water and heat exchanger network model with good bounding point and grid diagram of water and heat exchanger network model helps create the network (Sarut et al., 2014). The NLP model is used to initiate the topology of the water network with flowrate used for designing the optimal water network by MINLP model (Pungthong et al., 2015). Our work proposes the comparison between retrofit and grassroots design of water/wastewater network with MINLP model by using data of water using units from Savelski et al. (2003) and data of water treating units from Koppol et al. (2003).

Please cite this article as: Pungthong K., Siemanond K., 2015, The retrofit design for water network with multiple contaminants of industrial process, Chemical Engineering Transactions, 45, 1201-1206 DOI:10.3303/CET1545201

2. Problem statement

The problem in this paper is stated as the water/wastewater network model with multiple contaminants as shown in Figure 1 with water using units and treating units. It contains a set of water using units with fixed load of contaminants (Load $A_{i,j}$), maximum inlet (DA_j) and outlet (SA_i) concentration of each contaminants and a set of treating units with outlet concentration of each contaminants. The water utility is fresh water with zero contaminants (FW_j) and the concentrations of wastewater disposal are limited. The main purpose of this paper is to do retrofit design of water network with treatment and to do grassroots design of water/wastewater network compared with base case model of water network with treatment units by mathematical programming, GAMS. There are two designs in this case study: The retrofit design water network with treatment and the grassroots design of water/wastewater network.

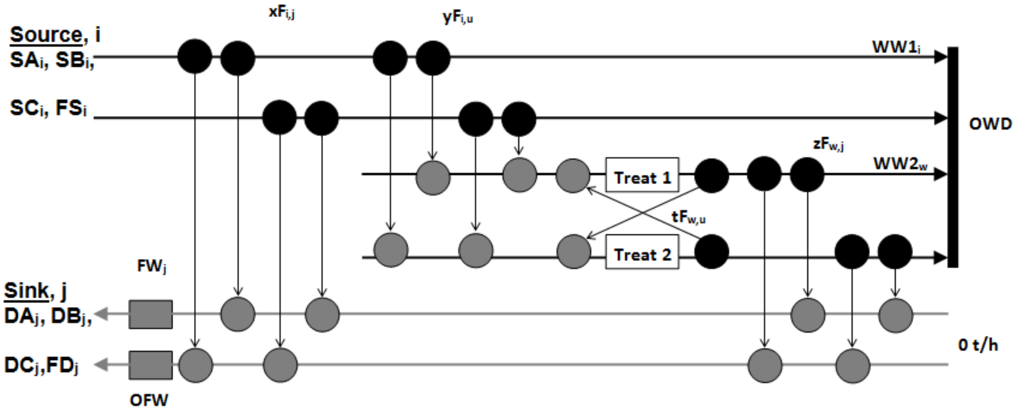

Figure 1: Grid Diagram of Water/wastewater network with three contaminants (A, B and C)

3. The retrofit design of water network with treatment

A base case consists of water network part and treatment units at end of process. The model consists of water network part from base case and retrofit design treatment part using a LP model as shown in Figure 2 under objective function to minimize total fixed cost (TFC) and total annual cost (TAC), cost of fresh water and cost of treatment water, with limited concentration of wastewater disposal while the water network part are fixed as base case.

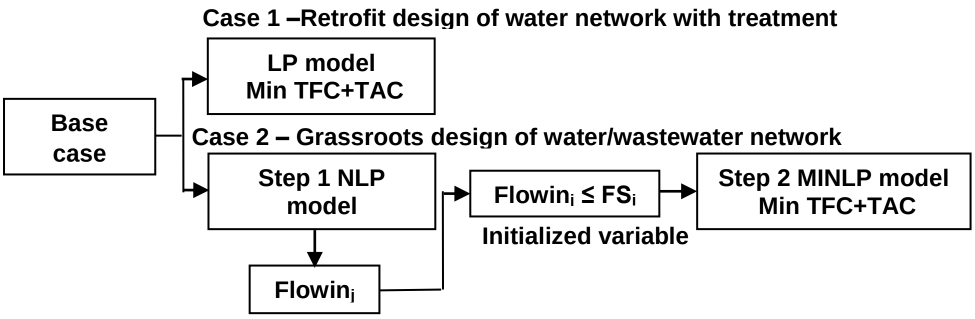

Figure 2: Design flow chart for retrofit design of water network and grassroots design of water/wastewater network with multiple contaminants

4. The grassroots design of water/wastewater network

The grassroots design of water/wastewater network is the redesign of base case model with the mathematical programming. The model consists of NLP model and MINLP model as shown in Figure 2. The proposed NLP model has initial point of lower-bounds for water flowrate of each process ($Flowin_j$) to generate the simple water network and $Flowin_j$ as a lower bound of flowrate of source i (FS_i) in MINLP model. The MINLP model is to generate water/wastewater network with not fixed topology of base case and the objective function is minimizing TFC and TAC. The payback period and net present value (NPV) are calculated from Eq(1) and Eq(2).

$$\text{Payback period} = \text{Total fixed cost} \div \text{Saving cost} \quad (1)$$

$$\text{NPV} = \sum[\text{Saving cost}_i \div (1 + \text{Annual interest rate})^i\,] - \text{Total investment cost} \quad (2)$$

where, i = life time (y)

5. Example

The example is a base case study from published work of Savelski et al. (2003) consisting of three process sources, three process sink with three contaminants; salt(A), organic (B) and H_2S(C), and data of three treatment processes from Koppol et al. (2003). The limiting data of water using part is shown in Table 1 and the data of treatment process is shown in Table 2. Cost of fresh water usage is 2.00 $/t, working time is 8,400 h/y and life time is 5 y. The piping cost data is shown in Table 3. The outlet concentrations of wastewater disposal (CWA, CWB and CWD) must be lower or equal 100 ppm.

Table 1: The allowable concentrations of contaminants in water using process

Process	Contaminant Types	Mass load (k/h)	C_{in}^{max} (ppm)	C_{out}^{max} (ppm)
1	A	0.675	0	15
	B	33.184	0	400
	C	54.821	0	35
2	A	3.4	20	120
	B	414.8	300	12,500
	C	4.59	45	180
3	A	5.6	120	220
	B	1.4	20	45
	C	520.8	200	9,500

Table 2: The allowable concentrations of contaminants in treatment process

Treatment Process	Contaminant Types	C_{out}^{max} (ppm)	Cost ($/t)
1	A	50	0.12
	B	Not treated	
	C	Not treated	
2	A	Not treated	0.56
	B	5	
	C	Not treated	
3	A	Not treated	1.00
	B	Not treated	
	C	20	

Result of base case, retrofit design of water network with treatment and grassroots design of water/wastewater network are shown in Table 4. The LP model generates treatment network in retrofit design of water network as shown in Figure 4 compared to base case as shown in Figure 3. The TAC of retrofit design (3.206 M$/y) is lower than base case (3.263 M$/y) because treating water in retrofit design is reduced from 105.59 t/h to 88.763 t/h and saving cost is 0.237 M$/yr. The TFC of retrofit design (12,200 $) is lower than base case (12,600 $) while the total investment cost of retrofit design is increased to 800 $. The MINLP model generates new water/wastewater network design with the lowest TAC of 2.141 M$/y and the highest saving cost of 1.122 M$/y while the TFC (14,300 $) is higher than base case and retrofit design. The grid diagram of grassroots design of water/wastewater network is shown in Figure 5. From the comparison between retrofit and grassroots design of water/wastewater network, the NPV during

5 y of grassroots design (4.2457 M$) is higher than retrofit design (0.8976 M$) and payback period of grassroots design is 0.0127 y and 0.0515 y in retrofit design.

Table 3: Piping fixed-cost data

Source i to Sink j		Treat w to treat u	
$xF_{i,j}$	**Fixed Cost ($)**	**$tF_{w,u}$**	**Fixed Cost ($)**
$xF_{1,1}$	1,100	$tF_{1,1}$	1,100
$xF_{1,2}$	1,300	$tF_{1,2}$	1,300
$xF_{1,3}$	1,500	$tF_{1,3}$	1,500
$xF_{2,1}$	800	$tF_{2,1}$	800
$xF_{2,2}$	1,000	$tF_{2,2}$	1,000
$xF_{2,3}$	1,200	$tF_{2,3}$	1,200
$xF_{3,1}$	1,100	$tF_{3,1}$	1,100
$xF_{3,2}$	1,200	$tF_{3,2}$	1,200
$xF_{3,3}$	1,000	$tF_{3,3}$	1,000
Source i to treat u		**Treat w to sink j**	
$yF_{i,u}$	**Fixed Cost ($)**	**$zF_{w,j}$**	**Fixed Cost ($)**
$yF_{1,1}$	1,200	$zF_{1,1}$	1,200
$yF_{2,1}$	1,100	$zF_{2,1}$	1,100
$yF_{3,1}$	900	$zF_{3,1}$	900
Source i to waste		**Treat w to waste**	
$WW1_i$	**Fixed Cost ($)**	**$WW2_w$**	**Fixed Cost ($)**
$WW1_1$	800	$WW2_1$	800
$WW2_2$	1,000	$WW2_2$	1,000
$WW2_3$	1,200	$WW2_3$	1,200
Freshwater FW to sink j			
FW_j	**Fixed Cost ($)**		
FW_1	1,000		
FW_2	1,200		
FW_3	1,400		

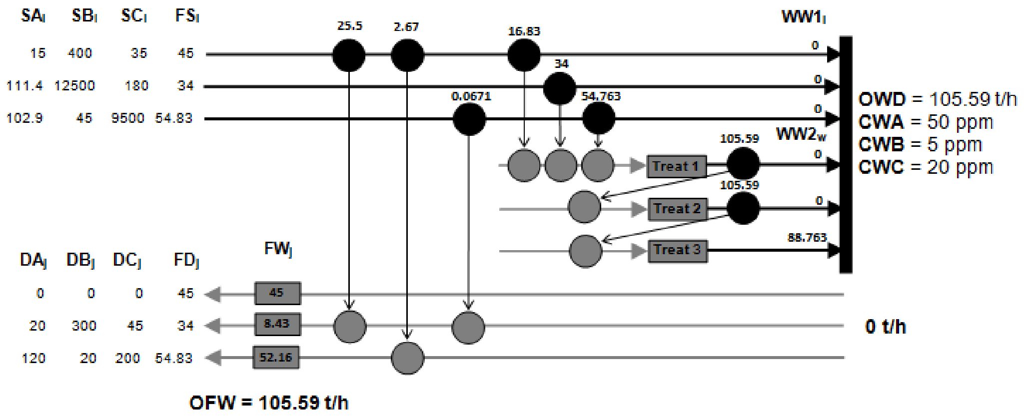

Figure 3: Grid diagram of Base case water network with the treatment (Treat1, Treat2 and Treat3) at the end

Table 4: Results comparison

Result	Base Case	Case 1 Retrofit design	Case 2 Grassroots design
FW_j (t/h)	$FW_1 = 45.000$ $FW_2 = 8.430$ $FW_3 = 52.160$	$FW_1 = 45.000$ $FW_2 = 8.500$ $FW_3 = 52.162$	$FW_1 = 45.000$ $FW_2 = 2.602$
$Flowin_j$ (t/h)	$Flowin_1 = 45.000$ $Flowin_2 = 34.000$ $Flowin_3 = 54.830$	$Flowin_1 = 45.000$ $Flowin_2 = 34.000$ $Flowin_3 = 56.000$	$Flowin_1 = 45.000$ $Flowin_2 = 34.000$ $Flowin_3 = 56.000$
$xF_{i,j}$ (t/h)	$xF_{1,2} = 25.500$ $xF_{1,3} = 2.670$ $xF_{3,2} = 0.061$	$xF_{1,2} = 25.500$ $xF_{1,3} = 2.670$ $xF_{3,2} = 0.061$	$xF_{1,2} = 25.425$ $xF_{1,3} = 2.019$ $xF_{3,3} = 1.060$
$yF_{i,u}$ (t/h)	$yF_{1,1} = 45.000$ $yF_{2,1} = 34.000$ $yF_{3,1} = 54.763$	$yF_{2,1} = 34.000$ $yF_{3,1} = 54.763$	$yF_{1,1} = 6.106$ $yF_{2,1} = 34.000$ $yF_{3,1} = 54.940$
$zF_{w,j}$ (t/h)	-	-	$zF_{3,2} = 5.972$ $zF_{3,3} = 52.921$
WW_i (t/h)	$WW2_3 = 105.590$	$WW1_1 = 16.830$ $WW2_3 = 88.763$	$WW1_1 = 11.449$ $WW2_3 = 36.153$
OFW (t/h)	105.590	105.590	47.602
Waste disposal (t/h)	105.590	105.590	47.602
Treated water (t/h)	105.590	88.763	95.046
TAC (M$/y)	3.263	3.026	2.141
Saving Cost (M$/y)	-	0.237	1.122
TFC ($)	12,600	12,200	14,300
Total investment cost ($)	-	800	1,700
Payback period (y)	-	0.0515	0.0127
NPV (M$)	-	0.8976	4.2457

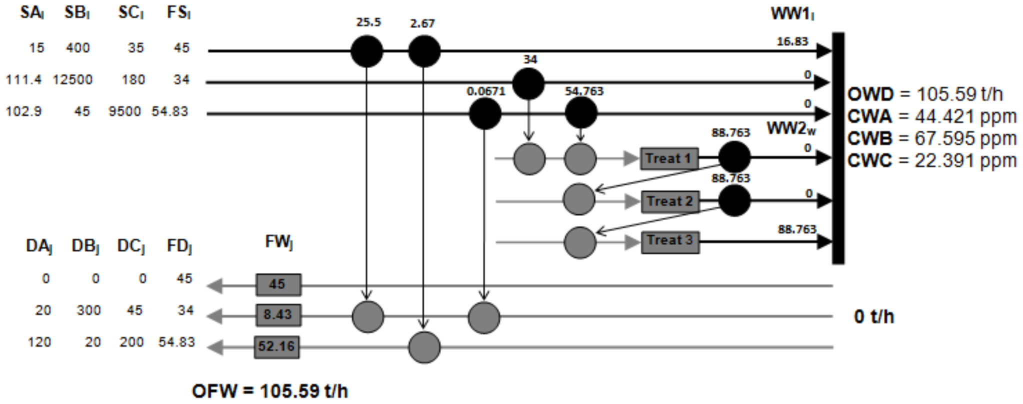

Figure 4: Grid diagram of case 1 - Retrofit design of water network with the treatment (Treat1, Treat2 and Treat3) at the end

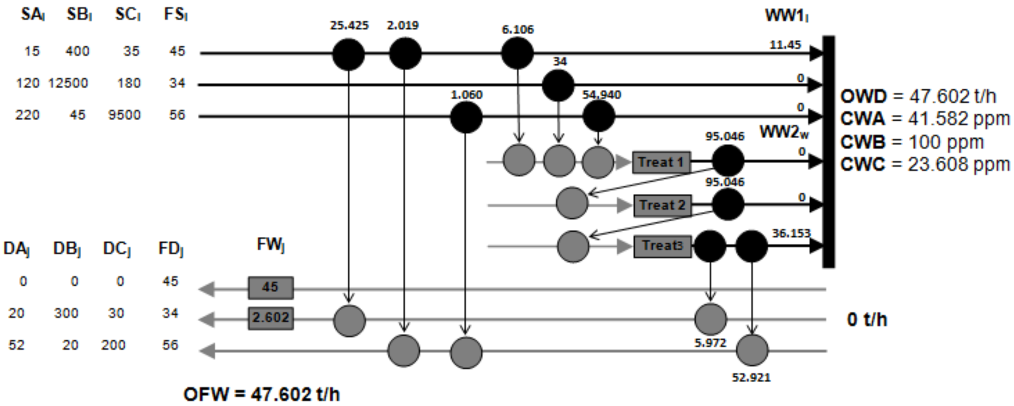

Figure 5: Grid diagram of case 2 – Grassroots design of Water/wastewater network

6. Conclusions

The MINLP model with NLP model as initial calculation step is simultaneous design of both network in water using process and wastewater treating. The grassroots design of water/wastewater network has better results in term of TAC, saving cost and NPV than the retrofit design of water network with the treatment. However in the industrial process, they can choose one of these designs to improve their water network. If they do not want to pay more fixed cost they can use retrofit design of water network. On the other hand, if they want to reduce more TAC they can use grassroots design of water/wastewater network.

Nomenclature

FS_i	Source flowrate (t/h)	$tF_{w,u}$	Transfer flowrate w to u (t/h)
SA_i	Source concentration of A (ppm)	$zF_{w,j}$	Transfer flowrate w to j (t/h)
SB_i	Source concentration of B (ppm)	FW_j	Freshwater flowrate (t/h)
SC_i	Source concentration of C (ppm)	OFW	Overall freshwater flowrate (t/h)
FD_j	Sink flowrate (t/h)	$WW1_i$	Waste flowrate from source i (t/h)
DA_j	Sink concentration of A (ppm)	$WW2_w$	Waste flowrate from treatment w(t/h)
DB_j	Sink concentration of B (ppm)	OWD	Overall wastewater disposal (t/h)
DC_j	Sink concentration of C (ppm)	CWA	Waste concentration A (ppm)
$xF_{i,j}$	Transfer flowrate i to j (t/h)	CWB	Waste concentration A (ppm)
$yF_{i,u}$	Transfer flowrate i to u (t/h)	CWC	Waste concentration A (ppm)

Acknowledgements

Authors would like to express our gratitude to the Petroleum and Petrochemical College, Chulalongkorn University, The Center of Excellence on Petrochemical and Materials Technology, PETROMAT and Government Budget Fund for funding support.

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