CHEMICAL ENGINEERING TRANSACTIONS Volume 25, 2011
Editors Jiří Jaromír Klemeš, Petar Sabev Varbanov, Hon Loong Lam
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DOI: 10.3303/CET1125094

Structure Optimization Method for Flexible Water Usage Network with Many Contaminants

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Optimization of the water using network (WUN) leads to optimum solutions only for certain process parameters. Changing the parameters makes necessary changing of the flow rate in the network connections. Due to specific structure and limits of the flow rate, these changes often result in a non-optimum control of the network. Additionally, changes of the WUN structure are expensive and require interrupting the water supply. That is why, there is a need to anticipate all possible alterations of the process parameters and design the WUN in such a way that the optimum flow control of the processing water is possible. Principles and assumptions of such a design method were presented in Poplewski and Jeżowski (2009). In this paper the design method of the optimum flexible WUN (FWUN) structure is presented.

1. Introduction

The typical data required to design WUN include mass loads of contaminants that have to be transferred in each water using process. They are highly uncertain in nature. Majority of designing approaches use fixed nominal values of these loads. Due to uncertain character of the parameters the solutions may be far from optimum or even they may be inoperable. Relatively few papers accounted for uncertain data. Suh and Lee (2002) are the authors of seminal work on WUN with considerations of uncertain data. They developed an approach for designing robust network. Koppol and Bagajewicz (2003) presented an approach for assessment of financial risk caused by uncertain data. To generate a flexible network they applied simultaneous method. Foo et al. (2006) analysed influence of uncertain data on WUN design. Riyanto and Chang (2010) developed a novel heuristic strategy to improve the operation resiliency of any existing water network by relaxing the active constraints identified in the optimal solution of flexibility index model. In this contribution we will describe a systematic approach for designing a structure of flexible WUN (FWUN).

2. Problem description

The method of optimum synthesis FWUN presented in this paper applies to the networks that include processes of a „mass load" type. Process inputs are:

- $L_p^{s,min}$, $L_p^{s,max}$ – minimum and maximum mass load of contaminants s for p processes. In case lack of anticipated changes of this parameter for a given process p and contaminant s a value of L_p^s is given.

Please cite this article as: Poplewski G. , 2011, Structure optimization method for flexible water usage network with many contaminants, Chemical Engineering Transactions, 25, 563-568
DOI: 10.3303/CET1125094

- $C_p^{s,in,\ max}$, $C_p^{s,out,\ max}$ – maximum magnitude of contaminant concentration s in the processing water on the inlet and outlet of the process p.

The goal is to find such a FWUN for which:

- the minimum usage of fresh water is maintained for all combinations of L_p^s lying between extreme values, that means for any possible process disturbance,
- the minimum number of connections is obtained – simple structure is certainly much easier to control, additionally, it is less demanding for the investment cost of the network building.

3. A method for problem solution

A solution method is based on a theorem of the corner solutions. According to it a network that is optimum for all practically possible combinations of extreme values of selected parameters (corner points) is also optimum for any value of these parameters if they are selected from an assumed range.

Simplified algorithm of a FWUN design method is as follows:

a. define all possible combinations of maximum disturbances – corner points,
b. for each corner point *l* determine possibly large number of solutions with a minimum usage of fresh water and possibly small number of connections in the network,
c. for each corner point select one solution in such a way that the number of types of connections in the FWUN is minimum,
d. based on flow rate in selected subnetworks determine maximum mass rate of flow for each connections within target network,
e. verify that obtained network is correct,
f. define method of control the network –flow rate in particular connections for all possible values of process disturbances.

In order to build FWUN one must know *k* optimum solutions for all possible *L* corner points (item 'b' of algorithm). These solutions must be optimum for a minimum usage of a fresh water. They should be also optimum or reasonably close to optimum for a minimum number of connections in the network. However, they are different within structure of connections and/or flow rate in particular network connections. A method of finding these solutions using ARS algorithm was presented in Jeżowski et al. (2007). In this paper only step „c" of the algorithm is presented. In the method it was assumed that FWUN structure must have all connections that are present in at least one optimum network for each of the corner point. Additionally, it must have a minimum number of connections within the network. That is why this is an IP type of optimization problem. The number of combinations of all *k* structures within *L* corner points is huge even for a fairly simple problem. Therefore it is not possible to solve it manually. In order to solve this step of the FWUN design the program GAMS was used.

4.Optimization model

In the presented method the goal function (1) minimizes the total number of connections FWUN.

$$GF = \min\left(\sum_{p\in P} Y_{FW,p}^{FWUN} + \sum_{p,p'\in P} Y_{p,p'}^{FWUN} + \sum_{p\in P} Y_{p,FT}^{FWUN} \right) \tag{1}$$

where:

$Y_{FW,p}^{FWUN}, Y_{p,p'}^{FWUN}, Y_{p,FT}^{FWUN}$ - binary variables that define presence of particular connection in the FWUN; FW -fresh water, p,p' - water using processes, FT - final treatment system. Some constraints are also necessary. The constraint (2) enforces selection of the only one solutions that is part of FWUN structure for each corner point.

$$\sum_{k\in K} Y^{k,l} = 1;\ l\in L \tag{2}$$

where:

K – set of solutions with different structure in a given corner point

L – set of corner points

Inequality constraints (3)-(8) introduce relationships of the binary variables that define FWUN structure with the substructures of the network for particular corner points.

$$\sum_{l\in L}\sum_{k\in K}\left(Y^{k,l}\cdot Y_{p,p'}^{k,l}\right) \le const\cdot Y_{p,p'}^{FWUN}\ ;p,p'\in P \tag{3}$$

$$\sum_{l\in L}\sum_{k\in K}\left(Y^{k,l}\cdot Y_{FW,p}^{k,l}\right) \le const\cdot Y_{FW,p}^{FWUN}\ ;p\in P \tag{4}$$

$$\sum_{l\in L}\sum_{k\in K}\left(Y^{k,l}\cdot Y_{p,FT}^{k,l}\right) \le const\cdot Y_{p,FT}^{FWUN}\ ;p\in P \tag{5}$$

$$\sum_{l\in L}\sum_{k\in K}\left(Y^{k,l}\cdot Y_{p,p'}^{k,l}\right) \ge 1+\left(const\cdot\left(Y_{p,p'}^{FWUN}-1\right)\right);p,p'\in P \tag{6}$$

$$\sum_{l\in L}\sum_{k\in K}\left(Y^{k,l}\cdot Y_{FW,p}^{k,l}\right) \ge 1+\left(const\cdot\left(Y_{FW,p}^{FWUN}-1\right)\right);p\in P \tag{7}$$

$$\sum_{l\in L}\sum_{k\in K}\left(Y^{k,l}\cdot Y_{p,FT}^{k,l}\right) \ge 1+\left(const\cdot\left(Y_{p,FT}^{FWUN}-1\right)\right);p\in P \tag{8}$$

where:

$Y_{FW,p}^{k,l}, Y_{p,p'}^{k,l}, Y_{p,FT}^{k,l}$ - values determined connections presence in the k network of l corner point,

$Y^{k,l}$ - binary variable defining structure that will be a part of FWUN,

$const$ – constant of magnitude higher than k.

For the illustrative example presented in the paper the number of inequality constraints (3)÷(8) was 808.

In the Table 1 it is presented an analysis of the influence of the presence of connection in the k structures on the magnitude of Y^{FWUN}. The value of left side of the inequality

(LSI) that equals zero means that in none selected solution for all Lcorner points a given connection does not exists.

Table 1: The effect of value of left side of inequality on magnitude of variable Y^{FWUN}.

	$LSI = 0$	$LSI \geq 1$
Value $Y^{FWUN}_{FW,p}, Y^{FWUN}_{p,p'}, Y^{FWUN}_{p,FT}$ that meets inequalities (3)÷(5)	0 or 1	1
Value $Y^{FWUN}_{FW,p}, Y^{FWUN}_{p,p'}, Y^{FWUN}_{p,FT}$ that meets inequalities (6)÷(8)	0	0 or 1
Value $Y^{FWUN}_{FW,p}, Y^{FWUN}_{p,p'}, Y^{FWUN}_{p,FT}$ that meets inequalities (3)÷(8)	0	1

5. Illustrative example

In the example the disturbanted parameter was the mass load of contaminants A and B in process P2 and contaminant C in process P3. All data were presented in Table 2.

Table 2: Data for illustrative example

p	s	L_p^s [kg/h]	$C_p^{s,in,\max}$ [ppm]	$C_p^{s,out,\max}$ [ppm]
1	A	0.675	90	120
	B	18	50	450
	C	1.575	75	130
2	A	6.1 ÷ 6.7	20	60
	B	41.8 ÷ 43.9	300	450
	C	4.59	90	230
3	A	5.6	120	220
	B	1.4	200	270
	C	52 ÷ 62.4	200	950

Due to fact that values were varied for 3 contaminants the number of all possible extreme combinations of the parameter (corner points) equals 8. They are presented in Table 3.

For presented example 10 different structures were obtained with use of method described in Jeżowski et al. (2007). Due to limitations of the paper all obtained structures are presented together in Table 4. The number in the Table 4 means that a given connection is present in structure with the same number.

Certain structures are referenced in different corner points. The summary combinations of structures and corner points is presented in Table 5.

Structures highlighted with grey color (Table 5) were included to the optimum FWUN, optimum due to number of connections. One possible optimum structure, from all obtained in the example, is presented in Table 6. Marking "x" means that a given connection is present in the FWUN structure.

Table 3: Corner points

p	s	$L^s_{p,l}$ for all l corner points							
		1	2	3	4	5	6	7	8
1	A	0.675	0.675	0.675	0.675	0.675	0.675	0.675	0.675
	B	18	18	18	18	18	18	18	18
	C	1.575	1.575	1.575	1.575	1.575	1.575	1.575	1.575
2	A	6.1	**6.7**	6.1	6.1	**6.7**	**6.7**	6.1	**6.7**
	B	41.8	41.8	**43.9**	41.8	**43.9**	41.8	**43.9**	**43.9**
	C	4.59	4.59	4.59	4.59	4.59	4.59	4.59	4.59
3	A	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6
	B	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
	C	52	52	52	**62.4**	52	**62.4**	**62.4**	**62.4**

Table 4: Summary of network structures obtained in the example

		inlets			
		p1	*p2*	*p3*	*FT*
outlets	*FW*	1÷10	5,7,8,10	1,2,5,6,7,9,10	
	p1		1÷10	3,4,6,8,10	
	p2	9		1÷10	1÷10
	p3	2,3,7	1,4,5,6,8,9,10		1÷10

Table :. Presence of WUN structures for particular corner points (marking „x" means that a given structure is present)

		Structure number									
		1	2	3	4	5	6	7	8	9	10
Corner points	1		x			x	x			x	
	2	x				x					
	3		x	x		x					x
	4						x				x
	5	x				x					
	6	x	x			x		x			
	7				x				x		x
	8	x	x			x					

Additionally to lack of self-recycle connections (excluded arbitrary), the optimum FWUN structure does not have connections from processes 2 and 3 to1 and also from process 1 to the final treatment system. Structure of the network presented in Table 6 was additionally verified for 50 randomly generated disturbances. Results confirm it is valid and agrees with all assumptions taken for FWUN.

Table 6: Structure of optimum FWUN.

		inlets			
		p1	*p2*	*p3*	*T*
outlets	*FW*	x	x	x	
	p1		x	x	
	p2			x	x
	p3		x		x

6. Conclusions

In the paper the method of FWUN structure optimization based on theorem of corner solutions was presented. It was showed that the method was efficient and fairly simple. Obtained flexible networks of the process water met a condition of the minimum requirement for the fresh water. It was verified for a set of 50 random disturbances to the selected parameters of the processes. Additionally the number of FWUN connections was low therefore a cost of building the network was minimized and the system was easier to control. In order to obtain solution of the presented model the GAMS program was used, however it can be solved with any solver that is dedicated to optimization IP problem type.

Acknowledgement

The work was supported by grant no. N N209 033538 of the Polish Ministry of Science and Higher Education.

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