OPTIMIZATION FOR THE REHABILITATION OF INTEGRATED WATER NETWORK SUPERSTRUCTURE IN THE INDUSTRIAL APPLICATION

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Abstract

The development of industrial technology such as water network control should help to achieve multiple targets including production efficiency and water sustainability. Therefore, the rehabilitation between two batch operations or under the abnormal situation should be a must with the help of the optimal valve control. In this paper, a comprehensive methodology for the above purpose has been developed for IWNS(integrated water network superstructure). At first, a superstructure of water reuse network design will be optimally obtained based on the methodology from our previous study. It will satisfy the requirement of manufacturing multiple products according to their processing recipes. The water network system need to be cleaned between two batch operations and it should also have the capability of fast rehabilitation for some abnormal situation such as unexpected impurity in the process. The proposed methodology in this study will give the valve control strategy during the rehabilitation to satisfy the process requirement. It is an optimization problem to minimize both the rehabilitation time and resource consumption.

Keywords

optimization, water sustainability, production efficiency, process rehabilitation.

Introduction

The advanced manufacturing requires the processes to satisfy the external and internal requirements simultaneously. Externally, it should provide the quick respond to customer needs and market changes(Boyer, Leong, Ward & Krajewski, 1997; Kotha & Swamidass, 2000). Internally, the production efficiency and water sustainability have currently become two major targets for the industrial sectors to pursue. Therefore, the research for the sustainability and flexibility of water utility network operation in the industrial plants has been reported in the previous years (El-Halwagi & Manousiouthakis,1989 & 1990; Zhang & Sargent, 1994; Wang & Smith, 1994,1995a & 1995b; Olesen & Polley, 1997; Mann & Liu,1999; Chen & Wang, 2012; Bagajewicz, 2000; Bocanegra-Martínez, et.al, 2014; Kong, Li, Sangwan, Kulzick, Matei & Ariyur, 2016).

There are processes which rely on the water for the operation in many industries with water-using processes, such as many rinsing processing and electroplating production lines. Several working units with various recipes should be completed in the same superstructure of production line.

More and more plants are going to circulate or reuse the water continuously for the purpose of water sustainability. The normal manufacturing will have the recipe-based production tasks but they are dynamically assigned. Therefore the scenarios of water flowing in the network should reactively change within the integrated superstructure of multiple water reuse networks to target at the production efficiency as well as design and maintenance cost saving. If the production line is given different production tasks, one water operation network should be switched online to another one with minimal time delay. The impurity concentration should be monitored and low enough to satisfy the process requirement for all the operations and the rehabilitation should be conducted if the impurity concentration has been above the threshold limit. There are also some abnormal situations when the water has been polluted during the normal operation. For example, the corrosion or leakage will potentially introduce the chemicals from the other process streams to the water network. The installed sensors should quickly detect the situation and start the rehabilitation at once. The rehabilitation will be achieved through the valve manipulation to bring some fresh water and discharge the waste water, and this method will not need to empty the water in all the units. Another method is just to discharge the water from all the units and then refill them with fresh water again. The industry should target both the saving of freshwater consumption and the cutoff of wastewater generation amount as well. Therefore, the comparison of water consumption quantity should be made between the above mentioned methods.

However, the previous studies have almost exclusively given more attention to the identification of one structure-fixed water reuse network for the investigated process system(Alva-Argaez,et.al,1998; Galan & Grossmann, 1998; Huang, et.al, 1999; Yang, et.al,2000;Savelski & Bagajewicz,1999a,1999b,2000,2001 & 2003; Feng & Seider,2001; Manan, et.al, 2004; Feng, et.al, 2007 & 2008; Foo, 2009; Jodicke, et.al, 2001; Halle, 2002; Forstmeier,et.al, 2005; Majozi, et.al., 2006; Karuppiah & Grossmann, 2006 & 2008; Pillai & Bandyopadhyay, 2007, Ponce-Ortega, et.al., 2009a; Ponce-Ortega, et.al., 2009b; Lira-Barragan, et.al, 2011a & 2011b; Liu, et.al, 2011; Liu, et.al, 2012). Among these, Zhou et al. (2001) has conducted a case study to integrate two water reuse networks into one network for cyclic water-rinsing operations and Fu et al. (2012) provided a methodology to support the network combination on how to couple multiple work reuse networks into one production line and how to switch among these water reuse networks according to different manufacturing purposes. Therefore, there is apparently a lack of systematical study on how to restore the integrated water network superstructure in the process in order to satisfy the process requirement. Actually, the quest for this requirement is to accomplish the maximum structural and operational flexibilities of a water-using network with the minimization of the transition time from one water network to another and the quantity of freshwater consumption and wastewater generation during such transitions, which is extremely important for many industrial processes.

In this paper, a comprehensive methodology for the above purpose has been developed. At first, a superstructure of water reuse network design will be optimally obtained based on the methodology from our previous study(Fu, et.al., 2012). It will satisfy the requirement of manufacturing multiple products according to their processing recipes. The water network system need to be cleaned between two batch operations and it should also have the capability of fast rehabilitation for some abnormal situation such as unexpected impurity in the process. The proposed methodology in this study will give the valve control strategy during the rehabilitation to satisfy the process requirement. It is an optimization problem to minimize both the rehabilitation time and cleaning resource consumption.

Methodology

The general idea to solve the above problem is to set up the dynamic model according to the mass balance of impurity in the superstructure of integrated water network. It can behave as multiple and independent single water-source structures through manipulating open/close strategy of control valves. Each scenario will be suitable to the specific rehabilitation with the objectives of minimal dynamic transition time and minimal mass consumption. The mathematical equations will be talked as below.

(1) DAE based Model for the Dynamics of IWNS Rehabilitation

The transition operation of integrated water network superstructure is a dynamic process which will involve the modeling of the differential algebra equation based on the principle of mass balance. The model can be described by Eq.(1) where $C_i^{k\to l}$, $V_i^{k\to l}$, $F_{i,j}^{k\to l}$ and $VC_{i,j}^{k\to l}$ are the concentration of impurity at unit i, the volume of unit i, the volume flow rate from unit i to unit j and valve control matrix element from unit i to unit j during the transition from recipe k to recipe l. Assume the density of the fluid will be constant without the change with respective to the impurity concentration and the Eq. (2) can be generated. The initial condition of the impurity concentration $C_i^{k\to l}(0)$ and volume $V_i^{k\to l}(0)$ are given by Eq. (3) and (4), which are equal to $IV_i^{k\to l}$ and $IC_i^{k\to l}$ respectively. The volume flow rate among the units are also constants and $y_{i,j}^{k\to l}$ is the element of an N×N binary matrix $VC^{k\to l}$ during the transition from recipe k to recipe l in order to represent water stream flowing status from the i-th unit to the j-th unit which has been given by Eq. (5).

$$\frac{d\left(V_i^{k\to l}\right)}{dt} = \sum_{j\in J, j\neq i}\left(VC_{j,i}^{k\to l}F_{j,i}^{k\to l}\right) - \sum_{j\in J, j\neq i}\left(VC_{i,j}^{k\to l}F_{i,j}^{k\to l}\right) \quad (1)$$

$$\frac{d\left(C_i^{k\to l}V_i^{k\to l}\right)}{dt} = \sum_{i,j\in J, j\neq i}\left(VC_{j,i}^{k\to l}F_{j,i}^{k\to l}C_j^{k\to l}\right) - \sum_{i,j\in J, j\neq i}\left(VC_{i,j}^{k\to l}F_{i,j}^{k\to l}C_i^{k\to l}\right) \quad (2)$$

$$V_i^{k\to l}(0) = IV_i^{k\to l}, i\in J \quad (3)$$

$$C_i^{k\to l}(0) = IC_i^{k\to l}, i \in J \quad (4)$$

$$VC_{i,j}^{k\to l} = \begin{cases} 0 & \text{for no pipeline connection} \\ 1 & \text{for direct pipeline connection without valve control} \\ y_{i,j}^{k\to l} & \text{for direct pipeline connection with valve control} \end{cases} \quad (5)$$

(2) Numerical Model for the Dynamics of IWNS Rehabilitation

Since the numerical analysis method will be applied to solve the above dynamic model, the total time span T have been separated into TN time intervals based on the assumed time interval length of ΔT .The quantitative relationship among these three parameters can be described by Eq. (6). The further discretization can be taken to change the above Eq. (1) ~ Eq. (5) to the form of Eq. (7) ~ Eq. (8). The time instance of t is belonging to the set of time instance and all the parameter are assumed to follow the linear change in the time interval.

$$TN = 1 + \frac{T}{\Delta t} \quad (6)$$

$$V_{i,t}^{k\to l} = \left[\sum_{j\in J, j\neq i} \left(VC_{j,i}^{k\to l} F_{j,i}^{k\to l} \right) - \sum_{j\in J, j\neq i} \left(VC_{i,j}^{k\to l} F_{i,j}^{k\to l} \right) \right] \cdot \Delta T + V_{i,t-1}^{k\to l}$$

$$t \in \left\{ m \middle| 1 \le m \le TN, m \in N^* \right\} \quad (7)$$

$$C_{i,t}^{k\to l} = \left[\left(\sum_{j\in J, j\neq i} \left[VC_{j,i}^{k\to l} C_{j,(t-1)}^{k\to l} F_{j,i}^{k\to l} \right] - \sum_{j\in J, j\neq i} \left[VC_{i,j}^{k\to l} C_{i,(t-1)}^{k\to l} F_{i,j}^{k\to l} \right] \right) \cdot \Delta T + C_{i,(t-1)}^{k\to l} V_{i,(t-1)}^{k\to l} \right] \times \frac{1}{V_{i,t}^{k\to l}}$$

$$t \in \left\{ m \middle| 1 \le m \le TN, m \in N^* \right\} \quad (8)$$

(3) Optimization for IWNS Rehabilitation

The optimization model is developed to target the objectives of both the minimal rehabilitation time and minimal mass consumption (pure water and waste water). Each recipe will have its own requirement for the initial impurity concentration in the units before the starting of recipe operation. Thus, the developed methodology will be applied to each possibility of recipe transition iteratively. The optimization model has been built based on the previous introduced numerical model of Eq. (3) ~ Eq. (8) for each time intervals. The additional objective functions have been given by Eq. (9) and (10). The first objective function $J_1^{k\to l}$ of this model is to minimize the rehabilitation time used to satisfy the requirement of every unit of impurity concentration at the new recipe l during the transition from recipe k to recipe l . The discrete time method is used and it divides the concerned time horizon into TN small time periods. A binary variable, $Y_t^{k\to l}$ from recipe k to recipe l, is employed to indicate if the cleaning of all the units has met the requirement or not at the time period t. $Y_t^{k\to l}$ is 1 if all the impurity concentration requirement of the new recipe l at all the units in time period t has been satisfied; otherwise, $Y_t^{k\to l}$ is 0. Furthermore, the attention should be paid that once $Y_t^{k\to l}$ becomes 1 in time period t , all $Y_{t'}^{k\to l}$ ($t < t' \le TN$) in the following time periods should also be 1. Therefore, Eqs. (13) must be fulfilled. Therefore, the minimum recovery time which is used to return to the impurity concentration requirement can be modeled by Eq. (9). The second objective function $J_2^{k\to l}$ of Eq.(10) aims to minimize the total cost of the feed water consumption and waste water consumption during the transition from recipe k to recipe l. The parameters λ_1 and λ_2 are the cost for the unit volume of waste water generation and pure water consumption. Eq. (11) shows the constraint of logical relationship, where $RC_i^{k\to l}$ is the required concentration of impurity in the unit i from recipe k to recipe l and $C_{i,t}^{k\to l}$ is the real time concentration of impurity in the unit i at time period t from recipe k to recipe l ; U is a sufficient big number. Let $X_{i,t}^{k\to l}$ be a binary variable to represent whether the cleaning of unit i at time t from recipe k to recipe l has been sufficient to meet the requirement or not: i.e., $X_{i,t}^{k\to l}$ is 1 if it is satisfied; otherwise, $X_{i,t}^{k\to l}$ is 0. As aforementioned, $Y_t^{k\to l}$ is the binary variable indicating whether the cleaning of all the units has been accomplished at the time instance t or not, which has been guaranteed by the logic constraint of Eq.(12). $NI^{k\to l}$ is the number of units involved in the transition from recipe k to recipe l. If there is one unit which cannot satisfy the cleaning requirement, the overall unit cleaning can be regarded to be uncompleted. Furthermore, the attention should be paid that once $Y_t^{k\to l}$ becomes 1 in time period t , all $Y_{t'}^{k\to l}$ ($t < t' \le TN$) in the following time periods should also be 1. Therefore, Eqs. (13) must be fulfilled.

$$\min J_1^{k\to l} = \left(TN - \sum_{t\in ST} Y_t^{k\to l} \right) \cdot \Delta t \quad (9)$$

$$\min J_2^{k\to l} = \left(TN - \sum_{t\in ST} Y_t^{k\to l} \right) \cdot \Delta t \cdot \sum_{t\in ST} \left[\lambda_1 \sum_{i\in J, i\neq WW} \left(VC_{i,WW}^{k\to l} F_{i,WW}^{k\to l} \right) + \lambda_2 \sum_{j\in J, j\neq FW} \left(VC_{FW,j}^{k\to l} F_{FW,j}^{k\to l} \right) \right] \quad (10)$$

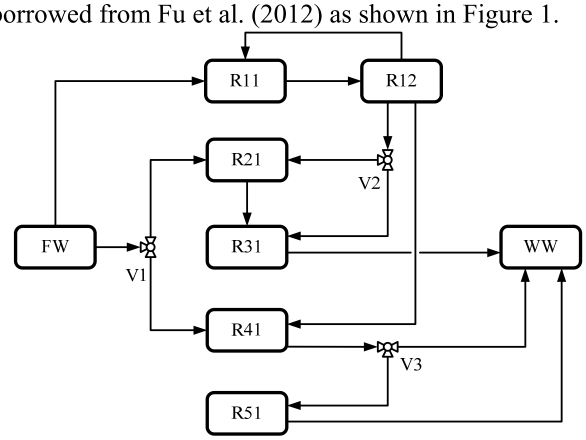
$$X_{i,t}^{k\to l} = \begin{cases} 1 & \text{for } C_{i,t}^{k\to l} \le RC_i^{k\to l} \\ 0 & \text{otherwise} \end{cases} \qquad (11)$$

$$Y_t^{k\to l} = \begin{cases} 1 & \text{for } NI^{k\to l} \le \sum_{i\in I} X_{i,t}^{k\to l} \\ 0 & \text{otherwise} \end{cases} \qquad (12)$$

$$Y_{t-1}^{k\to l} \le Y_t^{k\to l}, \quad t \in \{m | 2 \le m \le TN, m \in N^*\} \qquad (13)$$

Case Study

The case study is derived from the previous study of Zhou et al. (2001) and Fu et al. (2012). In the initial research by Zhou et al. (2001), the researchers have developed mathematical optimization modeling in order to achieve a switchable water allocation system with the maximum water reduction in a cyclic operation of an electroplating process. It is consisted of the primary network and the secondary network. The complete solutions are borrowed from Zhou et al. (2001). The latter research by Fu et al. (2012) have developed a systematic methodology to couple multiple water-reuse networks for the purpose of agile manufacturing. It can help to address the strategy of minimal number of regular and three-way valves with the optimal placement for the minimal total valve-switching times. The complete solutions are borrowed from Fu et al. (2012) as shown in Figure 1.



Network	Valve Control					
	V1		V2		V3	
	FW→R21	FW→R41	R12→R21	R12→R31	R41→R51	R41→WW
Primary Network	open	open	open	close	open	close
Secondary Network	close	close	close	open	close	open

Figure 1. Network integration solution from Fu et al. (2012)

In addition to the given network with different valve control strategy, the volume and the impurity concentration before/after each specific recipe have been assumed in below Table 1. All the feed water is assumed to have zero impurity concentration. The developed mathematical optimization models have been applied for the different transition. Furthermore, if the same recipe is processed continuously, the units in the network still need to be cleaned. The volumetric flow rates for the flows of FW-->R11, FW-->R21, FW-->R41, R11-->R12, FR12-->R11, R12-->R21, and R12-->R31 are 120L/min, 160L/min, 140L/min, 180L/min, 60L/min, 40L/min, 40L/min respectively for the opening status and the flow rates in the other pipeline can be calculated according to the open/close status of control valves. The other flow rates are set to keep the constant solution volume in the units.

Table 1. Parameter assumption for unit operation

Unit	Volume (L)	Impurity Concentration (mol/L)					
		Recipe A		Recipe B		Recipe C	
		Before	After	Before	After	Before	After
R11	2000	≤0.1	0.75	≤1	2	≤2	3
R12	2500	≤0.1	1	≤1	3	≤2	4
R21	2250	≤0.1	1.25	≤1	2	≤2	6
R31	3000	≤0.1	1	≤1	4	≤2	5
R41	2750	≤0.1	3	≤1	3	≤2	7
R51	3000	≤0.1	3.5	≤1	4	≤2	8

The results have disclosed that the rehabilitation time and pure water consumption will not be affected by the difference in the network integration solution. Based on the first level of multi-objective optimization model, the optimal valve control strategy with the corresponding rehabilitation time and water utility volume for all the rehabilitations have been listed in below Table 2.

Table 2. Optimization results(rehabilitation time & water consumption) for different recipe transition

Connection	A-->B	A-->C	B-->A	B-->C	B-->C	C-->A	C-->A	C-->B
Scenario	W/T	W/T	W/T	W	T	W	T	W/T
FW-->R21	open	close	open	Open	Open	open	open	open
R12-->R21	open	close	open	Open	Open	open	open	open
R12-->R31	close	close	close	close	Open	close	open	close
FW-->R41	close	open	open	Open	Open	open	open	open
R41-->R51	open	open	open	Open	Open	open	open	open
R41-->WW	open	open	open	Open	Open	open	open	open
Time(min)	64	34	171	44	43	193	191	102
Volume(L)	16640	4760	44460	11440	18060	50180	80220	26520

Connection	A-->A	B-->B	B-->B	C-->C
Scenario	W/T	W	T	W/T
FW-->R21	open	Open	Open	open
R12-->R21	open	Open	Open	open
R12-->R31	close	close	Open	close
FW-->R41	open	Open	Open	open
R41-->R51	open	Open	Open	open
R41-->WW	open	Open	Open	open
Time(min)	155	76	74	74
Volume(L)	40300	19760	31080	19240

The optimization results have disclosed that the rehabilitation time and pure water consumption can achieve the minimal target with the same valve open/close control strategy for the rehabilitations of A-->B, A-->C, B-->A and C-->B. However, for the rehabilitation of B-->C and C-->A, there are two scenarios which are oriented with only one target. It is clear to see that there is no big relative difference of the rehabilitation time between the time oriented scenario(with the symbol of T in Table 2) and water consumption oriented scenario(with the symbol of W in Table 2) in the comparison with the quantity of the water consumption. Therefore, the water saving oriented strategy has been selected in the next step to proceed the second level of optimization for multiple operation. The dynamic change trends for impurity concentration of all the units for optimal valve control strategy have been given in Figure 2 for the rehabilitation from B to A.

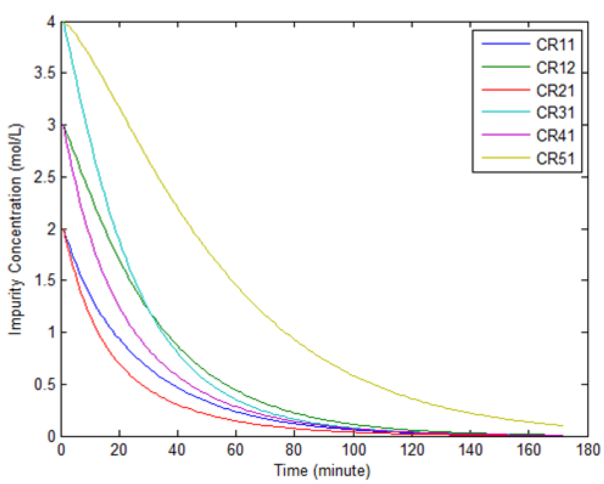


Figure 2. Dynamic change trend for impurity concentration in the units for optimal valve control strategy of recipe transition from B to A

Conclusion

A methodology has been developed to identify the optimal valve control strategy for the rehabilitation of integrated water network superstructure. It can help to achieve the requirement of short rehabilitation time and small quantity of freshwater consumption and wastewater generation for each recipe transition and response procedure for abnormal situation. The study is preliminary and general. Thus, it can be further extended to solve other problems of integrated water network superstructure.

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