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Design Method of Optimal and Flexible Water Networks with Regeneration Processes

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Optimisation of fresh water consumption in continuous water networks (WN) leads to the optimal solutions but not resistant to many kinds of changes and disturbances of process parameters. In cases where it is possible to predict the process changes and the extent disturbances of water parameters, from a practical and economic point of view flexible water network (FWN) should be designed.

In this work, solved problem of optimal design of FWN containing the source and sinks of process water as well as regeneration processes. Taken into account both the variation of the concentration of pollution in the regenerated water and periodic downtimes of selected sources and sinks.

To solve the problem algorithmic method based on the superstructure optimisation has been applied. This method uses theorem of corner points. FWN obtained with the method is characterized by minimal consumption of fresh water in all possible production situations. FWN also has minimum number of pipelines which has large impact on the investment cost. The method also gives insight into the possible flow rate in each pipeline. This information is fundamental for network designer to proper select of pipes diameters and ancillary equipment.

1. Introduction

Water is used for various purposes in the production processes in nearly all branches of industry. In large quantities it is also used in the chemical industry and in related industries such as the food industry. Growing demand, the price of water and scarce water supplies make it necessary to save natural resources. One of the ways to minimize the consumption of water taken from natural reservoirs (the fresh water) is reusing water in processes which don't have high purity requirements. Large number of papers has been published in the field of water network (WN) optimisation proposing many approaches to minimize water consumption, wastewater discharge and related costs. Reviews of the methods are given by Jeżowski (2010) and for Pinch methods by Foo (2009). In some cases, particularly when water is expensive or its resources are low, wastewater regeneration becomes cost effective. Another way to solve the problem is compromise allocation of resources. Method of optimal and compromise allocation of resources was proposed by Tan (2011).

The problem of optimal distribution of fresh water, water reused and regenerated water requires the use of optimisation or Pinch methods. The optimal WN is achieved under the assumption of parameters constancy of the water used in the processes and parameters of wastewater leaving processes. An example of uncertain data can be raw material supply and product demand. Optimisation approach for the synthesis of integrated biorefineries for this kind of uncertain data presented Tay et al. (2013). Fluctuations of flow rate, temperature and concentrations of pollutants in the process water are common in industrial plants. Zhang et al. (2009) has reported that "fluctuations in processing conditions can lead to process disruptions or product quality problem. So we must consider network resilience or flexibility during water network designing". These water parameters value changes are the reason for sub-optimal WN operation. Sometimes WN is not able to provide sufficient quantity and quality of water. This is due to the fixed structure of the WN and fixed, insufficient maximum flow rate in pipelines. WN retrofit in this case is very costly, among others because of the necessity of production downtime. From a practical point of view,

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flexible water networks (FWN) should be designed, that is, networks which are able to work optimally in all possible to predict cases. The FWN should also have possible simple structure and meet other criteria affecting the minimum investment and operating cost. It is very important that FWN should also be safety and reliability.

Optimisation of the water network need not be restricted to a single plant. Often is considered a water supply system for an eco-industrial park. Montastruc et al. (2013) proposed design method for the type of water network, taking into account several optimisation criteria: minimum consumption of fresh water, minimum flow rate of regenerated wastewater and the minimum number of pipelines. The authors then tested the influence of contaminants concentration fluctuations in each streams on WN flexibility. The authors concluded that the flexibility of the network increases with the number of pipelines. Unfortunately, this causes the investment cost increase too.

In this paper design method of FWN for given value of process parameters fluctuations has been proposed. Such method of design is better than checking the flexibility and cost-effectiveness of WN for certain design data. Fundamentals of the FWN design method used in this paper were presented by Poplewski and Jeżowski (2009) and later by Poplewski (2011). The aim of the present work is to demonstrate how the method can solve the more complex problem of designing FWN with sources, sinks and regeneration process fluctuations. Khor et al. (2014) has reported that “effluent quality in process plants typically indicates significant variability in the water source flow rates and contaminant concentrations as well as in the regenerator efficiency for contaminant removals”. The proposed in this paper method provides FWN which is able to work optimally for all possible combinations of process water parameters values. The method offers the possibility to take into account fluctuations of pollutants in regenerated water and water using processes downtimes. Except the structure of the FWN the method also provides information about minimum and maximum flow rate for each pipeline. This is essential information for proper selection of the diameter of pipelines and ancillary equipment during the final design of the FWN. The results obtained in the paper demonstrates a large adaptability of the method to the specific industrial requirements.

2. Problem description

Given are water sinks (j=1,…,N), water sources (i=1,...,M) and regeneration processes (r=1, ...,R) with a given concentration of the outlet water. For every sink we know concentration of the pollutant in the water stream and its flow rate. For every sink the data are the required water flow rate and the maximum concentration of impurities in the water. We assume that some processes may temporarily not work. That is why sometimes some sources will not offered water and some sinks will not use it. In addition, we assume that the concentration of pollutants in the water coming from the regeneration process may fluctuate. These fluctuations are within a specified range. Furthermore we assume that there is one source of freshwater and the quality of this water is known, i.e. concentrations of the contaminants in freshwater are the data. No limitations are imposed on concentrations of wastewater streams leaving the network.

The objective is to design FWN which will provide water with minimum operating cost in all possible cases, ie for all possible values of the water parameter. In addition, FWN must have as simple as possible structure, because an excessive number of pipelines unnecessarily increases the investment cost.

3. Problem solution

The solution method is based on theorem of the corner points proposed to solve the problem of resilient heat exchanger networks by Saboo and Morari (1984). According to the theorem 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.

Based on this theorem developed the following algorithm to solve the stated problem:

1. Assume combination of extreme values of uncertain parameters - a new corner point. Due to the fact that each uncertain parameter has upper and lower limits, the number of combinations is equal to 2^n, where **n** is the number of uncertain parameters.
2. For the current corner point find the optimal solution for the dominant objective function. The dominant objective function is mostly the operating cost that is in case of water network it is the cost of fresh water. In the discussed in this work example in addition to the cost of fresh water should also be taken into account the costs of waste water regeneration. The objective function of this algorithm step is:

$$OF = \min\left[\propto \sum_{j=1}^{N} F_{fw,j} + \beta \sum_{i=1}^{M} F_{i,FT} + \gamma \sum_{i=1}^{M} \sum_{r=1}^{R} F_{i,r} + \delta \sum_{r=1}^{R} F_{r,FT}\right] \quad (1)$$

where:

fw - fresh water,
FT - final treatment,
α - fresh water cost, [\$/t],
β - treatment cost, [\$/t],
γ - regeneration cost, [\$/t],
δ - regenerated water treatment cost, [\$/t].

Since the objective function is linear and uncertain data values taken in the first step are treated as constants, the model is linear and does not contain discrete variables. The problem in the stage is therefore the LP type.

3. Assume obtained in 2nd point value of the objective function as the upper limit. The minimum value of the objective function (1), adopted as the upper limit prevents obtaining WNs with sub-optimal operating cost.

4. Using integer cut conditions start the process of optimising the structure of WN repeatedly until all the water structure networks with the minimum number of pipelines will not be known. Save the flow-rates too. More optimal WNs generated for each corner point, gives a greater chance for the simplest structure of FWN. The objective of this step is the minimum number of pipelines in networks. Due to the form of the objective function and the use of integer cut conditions, it was necessary to introduce binary variables into the optimisation model. Thus the problem in this step is MILP type.

5. If the problem is not solved for all corner points, go back to step 1.

6. Based on all WNs obtained for all corner points find the FWN with possibly simple structure. Searching the simplest structure of FWN consists of optimum selection of WNs, one for each corner point. Selected WNs are numerically imposed on each other, which gives the structure of FWN. For the simplest structure FWN, imposed WNs should be structurally similar to each other. No continuous variables in this step causes the problem is IP type. Detailed procedure of optimising the structure of FWN for this stage was presented by Poplewski (2011).

7. Set the water flow rate ranges for each FWN pipelines. There are taken into account extreme flow rate values for all selected WNs.

Thus solving algorithm consists several steps of optimisation. In most of them different is the form of the objective function and the type of optimisation problem. Due to the linear nature of the optimisation model in each step to solve the problem the GAMS deterministic methods were used. These methods provide high speed and reliability of calculations.

4. Example of application

4.1 Description and data

The example is taken from the work of Sorin and Bėdart (1999) and then slightly modified. In addition to the source of fresh water there are also available 5 internal sources of waste water with given concentration of pollution and specific flow rate (Table 1). This water can be regenerated, discharged to treatment or used by sinks with specific requirements of quality and quantity (Table 2). The costs of water treatment, regeneration and treatment of waste water are listed in Table 3.

Table 1: Sources data for the example

	Fresh water	Source 1	Source 2	Source 3	Source 4	Source 5	Regenerator
C_i [ppm]	0	100	140	180	230	250	30-45
F_i [t/h]	∞	{0, 50}	60	70	80	195	the same as in the inlet

Table 2: Sinks data for the example

	Sink 1	Sink 2	Sink 3	Sink 4	Sink 5	Sink 6	Regenerator	Treatment
C_j [ppm]	0	50	50	140	170	240	no upper bound	no upper bound
F_j [t/h]	{0, 50}	60	80	70	80	195	no upper bound	no upper bound

Table 3: Cost coefficients for the example objective function (1)

Fresh water cost (α) [$/t]	Treatment cost (β) [$/t]	Regeneration cost (γ) [$/t]	Water treatment after regeneration (δ) [$/t]
1.00	0.65	0.15	0.35

In the regeneration process fluctuations of pollutants concentration in the regenerated water are possible. The concentration varies from 30 ppm to 45 ppm (Table 1). In addition, in the installation there is process called process 1, consisting of sink 1 and source 1. Process 1 a few times per year is disabled and during this time it takes no water or generate wastewater. For this reason, the flow rate for the process (sink 1 and source 1) may accept two specific values 50 t/h and 0 t/h. In the example, there are therefore two types of uncertain data. The first type of data takes continuous values from the specified range. The second type takes two or more specific values. The aim is to design FWN with the minimum number of pipelines and possibility of working at minimum water supply cost for all possible values of uncertain data. Besides FWN structure we must also specify the flow rate intervals in each pipeline. This information is needed to correct choice the diameter of pipelines and pump characteristics curves.

4.2 Solution of the example and results analysis

Accordance with the theory of corner points uncertain data should be combined in all possible combinations (Table 4). Because the sink 1 and source 1 represent one process therefore they are dependent on each other and take the same values in the corner points. In the case of fluctuations in the regeneration process are taken into account extreme values of the concentration of impurities. For example, the first and second corner point in Table 4 correspond to situation when 1st process operating while in the regeneration process concentration can fluctuate.

As a result of solving the problem for the parameters of each corner point obtained many WNs, which statistics contains Table 5. This table included:

- The minimum operating costs of water intake, regeneration and waste water treatment,
- The minimum number of pipelines while the minimum value of the operating cost is met,
- The number of optimal WNs met the two above conditions.

It should be noted that in the case of 4th corner point taking into account the additional 26 WNs with 14 pipelines had no impact on the final structure of FWN. This fact confirms the acceptance of WNs only with a minimum number of pipelines to the stage of final determination of the FWN structure. It is very important that each of WNs has a different structure and therefore without optimisation is almost impossible to select such four WNs, which ensure the minimum number of pipelines in the FWN. As a result of the optimisation, to construct the optimal FWN 4 WNs were selected. The structure and the water flow rate for the WNs are presented in Tables 6-9.

Table 4: Corner points

Proces	Parameter	Corner 1	Corner 2	Corner 3	Corner 4
Sink 1	F_j [t/h]	50	50	0	0
Source 1	F_i [t/h]	50	50	0	0
Regenerator	C_i [ppm]	30	45	30	45

Table 5: Solutions statistics for all corner points

	Corner 1	Corner 2	Corner 3	Corner 4
Minimum of the objective function (1)	91.0	91.7	87.5	88.1
Number of pipelines in WNs	14	14	14	13 (14)
Number of WNs	4	7	7	1 (+ 26)

Table 6: The WN structure for 1^{st} corner point with flow rate values

	Sink 1	Sink 2	Sink 3	Sink 4	Sink 5	Sink 6	Regenerator	Treatment
Fresh water	50	30						
Source 1		30		10	10			
Source 2				55.6		4.4		
Source 3					70			
Source 4				4.4		75.6		
Source 5			7.3			115	72.7	
Regenerator			72.7					

Table 7: The WN structure for 2^{nd} corner point with flow rate values

	Sink 1	Sink 2	Sink 3	Sink 4	Sink 5	Sink 6	Regenerator	Treatment
Fresh water	50	30						
Source 1		30		10	10			
Source 2				55.6		4.4		
Source 3					70			
Source 4			1.9	4.4		73.6		
Source 5						117	78	
Regenerator			78					

Table 8: The WN structure for 3^{rd} corner points with flow rate values

	Sink 1	Sink 2	Sink 3	Sink 4	Sink 5	Sink 6	Regenerator	Treatment
Fresh water		14.6	62.6			2.8		
Source 1								
Source 2				39.1	20.9			
Source 3		10.9			59.1			
Source 4			17.4			62.6		
Source 5				15.5		129.6	49.9	
Regenerator		34.5		15.5				

Table 9: The WN structure for 4^{th} corner points with flow rate values

	Sink 1	Sink 2	Sink 3	Sink 4	Sink 5	Sink 6	Regenerator	Treatment
Fresh water		28.6	51.4					
Source 1								
Source 2			28.6		21.7	9.7		
Source 3		11.7			58.2			
Source 4				35.9		44.0		
Source 5						141.2	53.8	
Regenerator		19.7		34.0				

Minimum number of pipelines in the FWN is equal to 23. FWN structure and possible ranges of flow rates in pipelines are specified in the Table 10.

Table 10: The final FWN structure for example with minimum, maximum and fixed flow rate values

	Sink 1	Sink 2	Sink 3	Sink 4	Sink 5	Sink 6	Regenerator	Treatment
Fresh water	{0,50}	14.6-28.6, {30}	{0}, 51.4-62.6			0-2.8		
Source 1		{0,30}		{0,10}	{0,10}			
Source 2			0-28.6	0-39.1, {55.6}	{0}, 20.9-21.7	0-9.7		
Source 3		{0}, 10.9-11.8			58.2-59.1, {70}			
Source 4			0-17.4	0-36.0		44.0-62.6, 73,6-75.6		
Source 5			0-7.3	0-15.5		115-117, 129.6-141.2	49.9-53.8, 72.7-78.0	
Regenerator		{0}, 19.7-34.5	{0}, 72.7-78.0	{0}, 15.5-34.0				

Analyzing the results summarized in Table 10 it can be seen different types of piping operation. For example, for the connection source 1 - sink 2 there are only two possible values of the flow rate: 30 t/h and 0 t/h. In this case, the purchase of the pump is very easy and not expensive because the exact flow rate value is known. In the case of a pipeline source 4 - sink 6 is known that the pump will run always regardless of the uncertain parameters. These two ranges operation of the pump make it easy to find the optimal flow rate ensures minimal operating cost FWN. The method of finding the optimal parameters of FWN is not complicated and will be presented in a separate article. In turn, the pipeline between the source of fresh water and sink 2 works optimally at a flow rate of 30 t/h for the case when process 1 operates. When process 1 is not working the optimal flow rate of water is in range from 14.6 t/h to 28.6 t/h.

5. Conclusions

This article presents a systematic, multistage method for designing flexible water networks. Obtained FWN provides the correct operation for all possible cases of fluctuation (e.g. water regenerator) and in the case of a temporary downtime of some processes in the network. At the same time feasible is optimal operation of FWN due to the dominant operating cost. The structure of the obtained network is also the simplest which has a large impact on investment costs. To summarize the proposed method based on the corner points theorem, has extensive FWN design capabilities for many different cases of uncertain data.

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