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Waste Water Network Retrofitting through Optimal Placement of Regeneration Unit

Petrica Iancu, Valentin Plesu, Vasile Lavric
University Politehnica of Bucharest
Centre for Technology Transfer in Process Industries
1-7, Gh. Polizu Street, BldgA, Room A056, 011061 Bucharest, Romania
tel. + 40 21 4023916, fax: +40 21 3185900, e-mail: p_iancu@chim.upb.ro

Optimisation of Wastewater Network (WWN) became lately a multi-objective task involving supply water decrease, internal water reuse increase, energy reduction, piping topology improvement, all under the umbrella of up-to-date economical information and foreseeable trends. Most of current approaches investigated from literature are restricted to WWN topology optimisation considering only one task, or, if several are taken into consideration, they are aggregated into a single objective function.

This paper presents the optimisation of WWN for simultaneous minimisation of the fresh water consumption and optimal placement of the regeneration unit, through minimisation of active pipes' length. WWN is defined as an oriented graph where water-using units are knots and the pipes are the arches of the graph. The oriented nature is given by ranking the water-using units either by their freshwater consumption or specific loads. The performance of the approach is tested on an industrial example and the results are compared to previous approaches.

1. Introduction

As a water minimization approaches branch, retrofit of WWNs is of real interest for industrial customers in terms of supply water and/or wastewater, energy or capital savings. Retrofit approaches were developed in the last years for different industries, petroleum and oil refining WWNs being the most targeted. Several alternatives can be considered for retrofit problems: changes in operating conditions or in process, and/or re-design/addition of existent/new equipments, piping or layout (Grossmann et al., 1987). It is quite impossible to achieve an optimum retrofitted WWN without taking into consideration the various processes and equipment design constraints, which involve major modifications and long payback periods. WWN mathematical models used for retrofit should consider as physical constraints the placement of water sources, water-using units or site capacities which are fixed when dealing with installing of new pipes or removing the obsolete ones. Optimal retrofit means discriminating between all possible global pipes lengths with different unit prices according to the pipe types.

Dantus and High (1996) oriented their research on developing an economic evaluation to retrofit the chemical process for methyl chloride production, through water minimisa-

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tion. They developed a combined technique using process simulation, optimization, and economic analysis tools to formulate a mathematical model and compared different alternatives based on the net present value method. Huang et al. (1999), proposed a mathematical model for retrofitting a WWN of a chemical plant which combined centralised treatment and local regeneration. The supply water is available as purified water after various preliminary treatments. They report 7% freshwater savings considering some practical constraints and rerouting all the wastewater streams to the centralised treatment facility. Bagajewicz et al. (2000) developed an approach for the grassroots and retrofit design of WWNs with multiple contaminants from a refinery site. The retrofit constraints are adding new pipes and/or a pump. A reuse structure was introduced by assuming a sequence of processes and water/wastewater allocation taking place in such a way that a) each process has only as precursors the previous elements of the sequence, b) the maximum reuse rule applies for each member of the sequence. The piping costs were reduced tenfold. A high level optimisation model for retrofit of process networks using a multiperiod generalised disjunctive programming was proposed by Jackson and Grossmann (2001) as a new step in retrofitting of industrial sites using different evaluation criteria. Chen and Hung (2005) formulated the retrofit of a mass-exchange network problem similar to that of retrofitting heat-exchanger networks. Their model considers the trade-off between costs for the external mass separating agents, the reassignment of existing units, the cost for additional tray numbers, column heights, or both, and the cost for the installation of new units. Hul et al. (2007) solve a retrofit problem for optimisation of a paper mill WWN. They focused on development of a simple mathematical model and a fuzzy algorithm to reconcile the conflict between flowrates and cost optimisation cases and report an investment of with a payback times of 38 days. Tan et al (2007) retrofitted the paper mill WWN using new regeneration units instead of adding more mass exchangers and maximizing the operating costs' savings, subject to a minimum payback period or a maximum capital expenditure. Faria and Bagajewicz (2008) use mathematical optimisation to retrofit a WWN by maximizing net present value instead of freshwater consumption, for single and multicomponent problems.

This paper proposes the WWN retrofit under simultaneous minimisation of the fresh water consumption and active pipes' length, the latter through the optimal placement of the regeneration unit. An industrial example is used as test case and the results are compared with some previous approaches.

2. WWN modelling

2.1 The physical model

Given an existing water network with N water-using units, NS supply water sources, K contaminants to be removed and one wastewater regeneration unit, an optimal WWN topology is sought under the following restrictions: minimum supply water allocation from fixed sources, maximum internal water reuse, optimal placement of regeneration unit by minimization of the overall pipe length, fixed inlet/outlet maximum concentrations and mass load of contaminants transferred from process streams to water streams as well. The WWN is supplied from several water sources with different levels of contamination and its effluents can be discharged or sent to the regeneration unit, which has fixed outlet and is able to remove all contaminants (see Iancu et al., 2007 for a sketch).

2.2 The mathematical model

WWN is defined as an oriented graph where water-using units are knots and the pipes are the arches of the graph. The oriented nature is given by ranking the water-using units either by their freshwater consumption or their specific loads. The mathematical model is based upon the overall and species mass balances around water using unit and regeneration unit, together with the associated constraints (in terms of input and output maximum allowable concentrations) and specific constraints for the existing WWN. For optimal retrofit of WWN, simultaneous minimisation of the fresh water consumption and optimal placement of the regeneration unit, through minimisation of active pipes' length is considered. Using information about pipes lengths, a topological index criterion is defined as the ratio between the total active lengths (length of pipes used for transportation of supply water, internally reused water and wastewater discharge) and the total lengths of the piping system (overall length of pipes between sources and units, pipes between different units and pipes between units and treatment unit), as in Eq.1.

$$\tau = \frac{\sum\limits_{\substack{j=1 \\ F_j^S>0}}^{N} \mathtt{l}_{0,j} + \sum\limits_{i=1}^{N-1} \sum\limits_{\substack{j=i+1 \\ X_{i,j}>0}}^{N} \mathtt{l}_{i,j} + \sum\limits_{\substack{j=1 \\ W_j>0}}^{N} \mathtt{l}_{j,N+1}}{\sum\limits_{j=1}^{N} \mathtt{l}_{0,j} + \sum\limits_{i=1}^{N-1} \sum\limits_{j=i+1}^{N} \mathtt{l}_{i,j} + \sum\limits_{j=1}^{N} \mathtt{l}_{j,N+1}} \tag{1}$$

The objective function is defined as a linear combination between the normalised supply water flowrate and topological index. Weighting factor is denoted by ω, underlining the relative role of objective function components (Eq. 2). When ω=1, only the supply water flowrate is minimised. When ω=0, only the topological index is minimised. For 0<ω<1, a parametric study showing the different influences of each component upon the objective function is obtained. Knowing these influences, in practical situations, specific values for ω factor can be selected.

$$\min \mathrm{T} = \min \left(\omega \frac{\sum\limits_{i=1}^{N} \max \left(F_{i,in}^{s,\min} , F_{i,out}^{s,\min} \right)}{\sum\limits_{i=1}^{N} \max\limits_{\mathrm{k}} \left(\dfrac{m_{ki}}{C_{ki}^{\mathrm{out},\max} - C_{ki}^{in,\max}} \right)} + (1-\omega)\,\tau \right) \tag{2}$$

3. Case study and discussions

An industrial case study from a refinery site was selected to be retrofitted. Seven water-using units (U1, U2,…, U7) were setup for analysis together with their limiting data (inlet and outlet maximum compositions and mass loads for contaminants C1, C2, C3 and C4). A detailed presentation of the case, together with the physical model of WWN, is given in Iancu et al. (2007). Two water sources (freshwater and purified water) are available on the site (Table 1) and the length of pipes linking the WWN units, the sources to the units and the latter to the centralized treatment unit (T) are known (see Table 1). The GA optimisation technique is applied to retrofit WWN considering minimum supply water flowrate and minimum topological index as objective functions, using regeneration of some designated contaminants (as resulted from critical contaminant analysis). The optimal WWN topology resulted this way is compared with the base case.

Table 1 Pipes length for water network

L_{ij} (m)	S1	U1	U2	U3	U4	U5	U6	U7	T
S1	-	500	600	400	200	500	400	100	-
U1	500	-	300	100	500	200	200	100	500
U2	300	300	-	300	300	500	400	300	400
U3	100	100	300	-	250	100	300	200	300
U4	500	500	300	250	-	300	300	200	400
U5	200	200	500	100	300	-	800	600	200
U6	200	200	400	300	300	800	-	150	600
U7	100	100	300	200	200	600	150	-	500
T	-	500	400	300	400	200	600	500	-

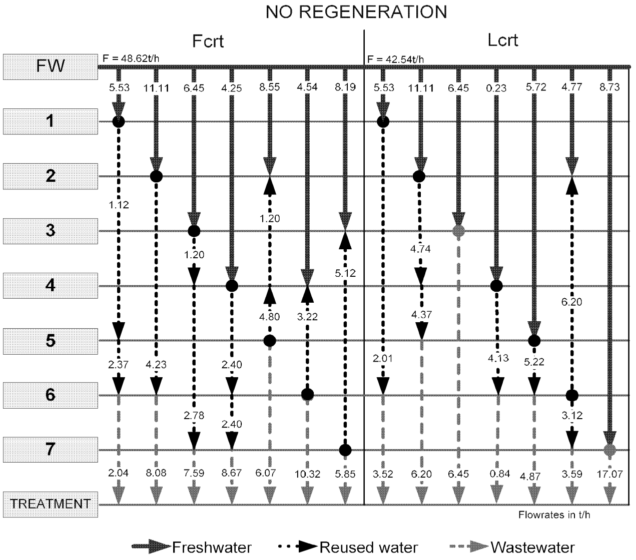

Figure 2 WWN topology for base case study

3.1 The base case: the water network is optimised considering only reusing strategy.

The WWN is abstracted as an oriented graph where the placement of water using units is given either by the level of supply water flowrates (Fcrt criterion) or by the mass loads (Lcrt criterium). After optimization using GA, the supply water flowrate is 48.62 t/h (Fcrt criterion) and 42.54 t/h (Lcrt criterion). The resulted new WWN topology is complex, many streams being reused, so 3150 m of additional pipes are needed, when using Fcrt criterion, and only 2850 m of supplemental pipes are need when using Lcrt criterion (see Figure 1). The minimum topological index gives information about how much of the total pipes length is actually used due to internal water reuse between units: 56.25 % for Fcrt criterion and 50.89 % for Lcrt criterion. Consequently, the topology is quite rigid and further improvement is expected.

3.2 Retrofitting case: the water network is optimised for simultaneous minimisation of the fresh water consumption and optimal placement of the regeneration unit, through minimisation of active pipes' length.

The allocation of effluents which are sent to regeneration (able to remove all contaminants from the wastewaters) was setup from critical component analysis proposed by the authors in Iancu et al. (2007). C2 was identified as critical component with minimum availability, but C3 has also a close value (Table 2). Thus, there is a bottleneck island of two critical contaminants which should be regenerated together, J3={C2,C3}. Supply water flowrate is reduced with 20-25% when the effluents of four water using units (U1, U3, U4, U7 for Fcrt criterion and U1, U2, U4, U6 for Lcrt criterion) are regenerated. The regenerated water flowrate is 19.34 t/h (Fcrt criterion), respectively 21.05 t/h (Lcrt criterion). The WWN topology is simplified compared to the base case since only 1750 m (Fcrt criterion) and 1800 m (Lcrt criterion) are needed to minimize the topological index. No further improvement was found regenerating another contaminants.

Table 2 Results summary

Scenario	Ranking Criteria	Supply water flowrate, t/h	Topological Index %	Mean Contaminant Availability, [ppm]			
				C1	C2	C3	C4
Base case	Fcrt	48.62	56.25	35.61	**14.75**	**14.73**	47.27
	Lcrt	42.54	50.89	37.02	**14.98**	**14.13**	46.47
Retrofitting case	Fcrt	38.55	31.25	37.24	31.23	13.35	47.15
	Lcrt	32.32	32.14	35.59	33.46	14.60	47.31

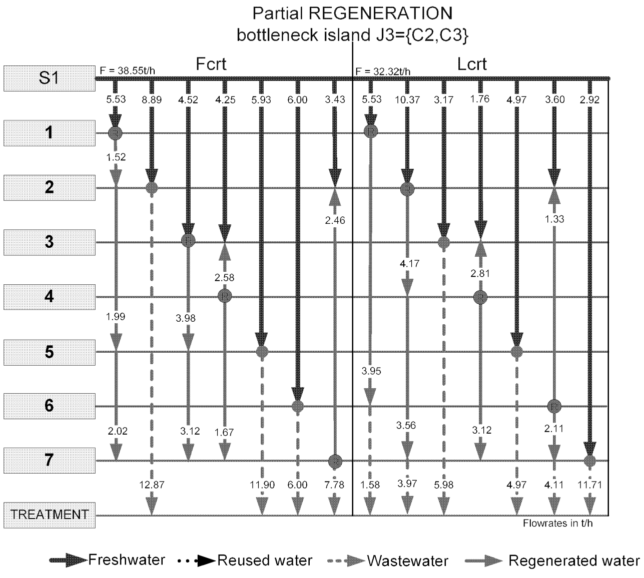

Figure 3 WWN topology for retrofitting case study

4. Conclusions

The retrofit of WWN was done, using the topological index and the supply water flowrate as objective functions to be minimized, considering the optimal placement of a regeneration unit. The WWN's physical model is an oriented graph, and this imposes the formulation of mathematical model. The case study tackles the important problem of retrofitting an existing WWN such to improve the total active pipes length, compared to the results obtained when only the increase of the internal reuse was formulated as strategy. Two different scenarios were analysed, employing as objective functions both the supply water consumption and the total active pipes length, which were minimized using and improved version of GA. The existence of a bottleneck island of two contaminants imposed the optimization of the WWN topology under the constraint of regenerating both of them as a whole. Under these circumstances, the supply water flowrate decreased by 20-25 %. Any attempt to improve the two topologies regenerating also the other two pollutants, not belonging to the bottleneck island, failed since even after regeneration their mean virtual mass driving forces (see Iancu et al, 2007 for the definitions) were still higher than the those of the bottleneck island's contaminants.

5. References

Bagajewicz M., Rivas M. and Savelski M., 2000, A robust method to obtain optimal and sub-optimal design and retrofit solutions of water utilization systems with multiple contaminants in process plants, Comp.Chem.Eng., 24(2-7), 1461-1466

Chen C.L. and Hung P.S., 2005, Retrofit of Mass-Exchange Networks with Superstructure-Based MINLP Formulation, Ind. Eng. Chem. Res. 44, 7189-7199

Dantus M.M. and High K.A., 1996, Economic Evaluation for the Retrofit of Chemical Processes through Waste Minimization and Process Integration, Ind. Eng. Chem. Res., 35, 4566-4578

Faria, D. C. and Bagajewicz, M J., 2008, Profit-based grassroots design and retrofit of water networks in process plants, doi:10.1016/j. compchemeng. 2008.10.005

Huang C., Chang C., Ling H., Chang C., 1999, A Mathematical Programming Model for Water Usage and treatment Network Design, Ind. Eng. Chem. Res., 38, 2666-2679

Iancu, P., Plesu, V., Lavric, V., 2007, Topological impact of regeneration unit constraints upon water and wastewater network, 17th European Symposium on Computer Aided Process Engineering-ESCAPE17, Bucharest, Romania, 27-30 May 2007, Computer-Aided Chemical Engineering, vol. 24, (Eds. Pleşu, V. & Agachi, S.), Elsevier, 1313-1318

Jackson J.R. and Grossmann I.E., 2002, High Level Optimization Model for the Retrofit Planning of Process Networks, Ind. Eng. Chem. Res., 41, 3762-3770

Seingheng H., Ng D.K.S., Tan R.R.,Chiang C.L. and Foo D.C.Y., 2007, Crisp and Fuzzy Optimisation Approaches for Water Network Retrofit, Chemical Product and Process Modeling, 2(3), 564

Tan Y.L., Manan Z.A. and Foo D.C.Y., 2007, Retrofit of Water Network with Regeneration Using Water Pinch Analysis, Trans IChemE, Part B, Process Safety and Environmental Protection, 85(B4), 305–317