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Energy Savings vs. Freshwater Consumption when Optimizing Total Wastewater Networks

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The dual-objective optimization of an integrated water/wastewater network (IWWN) is addressed in this paper, by targeting for simultaneous minimum fresh water consumption and investment and operating costs reduction of the pipeline system; the latter is a main component in energy savings opportunities. An IWWN is a recycle system composed of two oriented graphs, the first encoding the water-using units (WUs) and the second, the treatment units (TUs). Internal wastewater recycling is forbidden *ab initio* for the WUs graph, external recycles from the proper TU to the WU whose inlet restrictions are fulfilled by the partially treated water are favoured. In order to encourage this kind of recycling the critical contaminants for each wastewater internal flow are identified and assigned to the local regeneration unit, as a better alternative to complete decontamination. The corresponding mathematical model was written and assessed on a synthetic example. A thorough comparison is made highlighting the differences between the network's performances with respect to the features aforementioned for some points of the Pareto front.

Keywords: Integrated wastewater network, Fresh water minimization, Costs optimization, Regeneration, Multi-objective optimization, Pareto front

1. Introduction

Process integration of total water/wastewater networks enables the efficient use of freshwater taking into consideration the opportunities for wastewater reuse either directly or throughout treatment (end-pipe removal of contaminants to dispose the water in environment) or regeneration (partial removal of pollutants to increase local reuse). Since there are many ways of reusing, treating or regenerating wastewater to reuse it, thus decreasing freshwater consumption, the development of design targets for the minimum freshwater demand is crucial to assess alternatives. In the implementation of wastewater reuse, the beneficiary WUs will govern the degree of wastewater treatment required. A high degree of treatment would allow more wastewater reuse, which would in turn reduce costs associated with freshwater consumption at the expense of increased treatment costs and network complexity, which raises investment and operating costs. The right balance of these costs and freshwater minimization to achieve an optimal network is the objective of this study, taking into account their dichotomic nature.

Two main categories of methods are used to obtain good designs of IWWNs: pinch technology with all its derivatives and mathematical programming. The most recent and

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comprehensive review of the various graphical techniques to design and retrofit continuous water networks has been published by Foo, 2009.

The methods of water networks optimization based on mathematical modeling approach can be lumped into relatively few directions. Generally the main focus of researchers is on the optimization of one or multi-contaminant water networks disregarding the treatment section (Savelski and Bagajewicz, 2001), or taking it into consideration in the optimization of the IWWNs. Another direction of investigation is to consider partial/total regeneration of internal water streams in order to further reduce external freshwater demands as compared to the water networks with just direct water reuse/recycle (Koppol et al, 2003. Regeneration systems enhance water reuse potential by improving stream quality to suit water demands within process plants. This leads to further reduction of water flowrates in the network (Ng et al, 2007).

Another approach of the optimization of water networks was used by Lavric et al, 2007 and Iancu et al, 2009. The aim was to reveal the topological impact of regeneration unit upon a water network. The potential for internal regeneration, i.e. increasing the possibilities of internal wastewater reuse as a supplementary asset for the optimization of complex wastewater networks, was estimated by the introduction of some new concepts, i.e. regeneration of critical component, regeneration of bottleneck island, or partial/total regeneration strategy. Later, this approach was extended to optimization of an integrated WUs and TUs network for minimization of the freshwater consumption and the results analyzed with respect to two new concepts: mean availability and network reuse index (Tudor and Lavric, 2010b).

The same problem was addressed also by Tudor and Lavric (2010a) in which a model for the IWWN was applied to obtain the best topology, using Genetic Algorithms as the optimization strategy. This new optimization approach was used to minimize the freshwater consumption through maximization of internal and treated wastewater reuse.

In this paper we present a new approach on IWWN optimization which is able to identify the opportunities to increase the treated and regenerated wastewater reuse and to find the optimal network that ascertains energy savings alternatives (to which the piping network costs reduction belongs) and also overcomes problems like freshwater scarcity.

2. Mathematical model

An IWWN can be assimilated to a system of two oriented graphs with respect to water flow. The first graph starts with WUs with contaminant free constraints at their inlet, which are supplied with fresh water only. Any other WU could collect streams from all WUs, preceding it, and could send streams to all succeeding WUs. An IWWN can have different topologies, each corresponding to the optimization of a particular objective function, which encodes the performance criteria envisaged. The freshwater consumption, our first objective function, has been completely derived in Tudor and Lavric, 2010a. The second component of our dual-objective function, the investment and operating cost of the active pipe system, is based upon the cost of the unit length of a pipe linking two consecutive WUs and having the optimum economic diameter, as it was fully detailed in Lavric et al, 2007. These two objectives are dichotomic in nature, since minimizing the freshwater consumption means increasing internal wastewater reuse, i.e. the active pipe network complexity, thus the necessity of the Pareto approach.

3. Case study

Table 1: Primary data (mass loads, inlet and outlet restrictions) of the water-using units of the integrated network

UNIT No.	Load (kg/h)				Inlet concentration restrictions (ppm)				Outlet concentration restrictions (ppm)			
	Contaminant				Contaminant				Contaminant			
	1	2	3	4	1	2	3	4	1	2	3	4
WU1	315	210	248	215	0	0	0	0	35	38	27	32
WU2	320	290	185	130	10	8	12	15	63	49	39	102
WU3	450	380	273	360	15	12	18	16	81	73	87	80
WU4	280	210	340	350	14	18	20	16	80	78	95	100
WU5	410	320	380	425	12	10	10	18	75	70	100	150
WU6	210	315	375	335	20	23	25	20	100	92	120	135

A synthetic example was used to study both the optimal topology of an IWWN and which are the effects of the inclusion of the local regeneration unit upon the network and on the fresh water consumption. An original network of six WUs and four contaminants (the information regarding each unit's load and associated restrictions are shown in Table 1), three TUs (the inlet restrictions and the fixed outlet values of the concentrations of each contaminant are presented in Table 2) and one regeneration unit, RU, (the information regarding the constraints are listed in Table 3) is analyzed having as objective the identification of the optimum topology which reduces fresh water consumption together with the investment and operating costs for the pipe network, while increasing treated or regenerated wastewater reuse. The treatment units' inlet restrictions and outlet concentrations permit treated wastewater to cascade from TU1 till TU3. At the same time, the treated water from TU1 could feed WU6, the exit of TU2 could enter WU3, WU4 and WU6, while the treated water from TU3 could feed any WUs, except WU1, which is free of inlet contaminant at its entrance.

Table 2: Inlet restrictions and outlet settings of the treatment units

UNIT No.	$C^{in,min}$ (ppm)				C^{out} (ppm)			
	Contaminant				Contaminant			
	1	2	3	4	1	2	3	4
TU1	80	75	95	105	20	23	25	20
TU2	60	45	50	80	14	12	18	16
TU3	10	10	15	15	2	4	5	3

Table 3: Regeneration Unit constraints

Contaminant	Constraints, ppm	
	inlet	outlet
1	50	10
2	60	8
3	40	10

The present study tries to answer the question of the suitability of using a RU when there is a complex end-pipe treatment facility, which can be seen as well as a source of some mildly contaminated water supply for the WUs' network (Tudor and Lavric, 2010a, 2010b).

4. Results and discussions

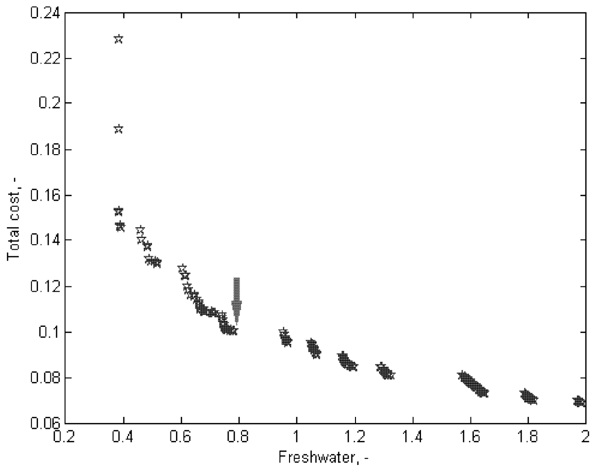

Figure 1: Pareto front for dual-objective optimization of the IWWN (a – freshwater use; b – investment and operating costs of the pipe network)

We apply in the present study the solving strategy presented in Tudor and Lavric (2010a, 2010b) enhanced with the way the RU is taken in consideration. Since regeneration means local treatment, we consider that if the exit of a WU qualifies for regeneration (its contamination level is greater that RU's inlet restrictions for all the pollutants), only the internal streams heading to the next WUs will be processed by RU, while the stream discharged to treatment will not be subject to regeneration – it will be decontaminated in the treatment facility anyway. At the same time, whenever possible, every WU will be fed with the appropriate water coming from TUs, rather than freshwater.

Taking into account the dichotomy between the two objectives simultaneously minimized, the result of the optimization is a Pareto front (PF) as depicted in Figure 1. Ana-

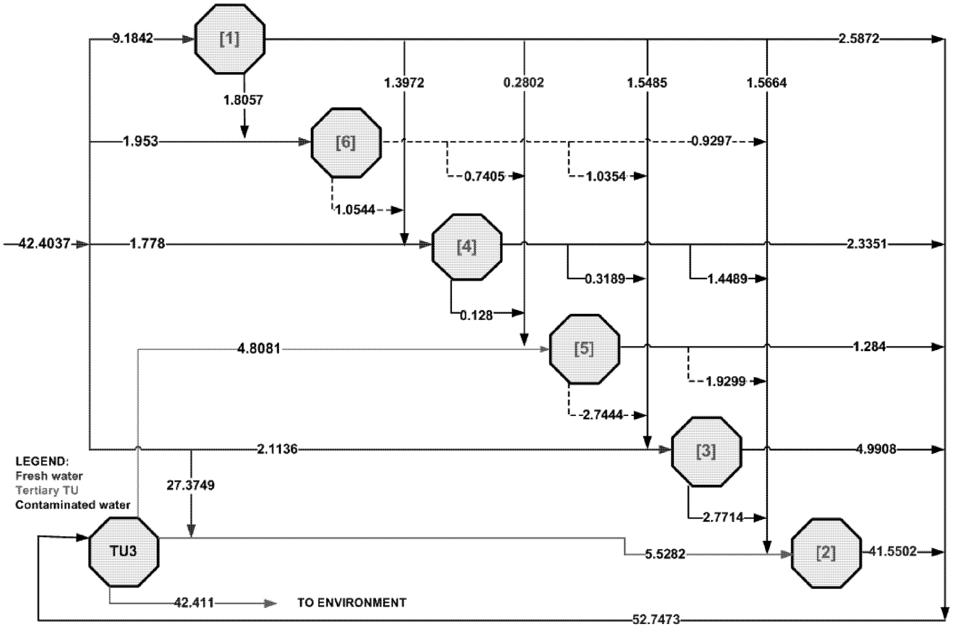

Figure 2: The topology of the IWWN corresponding to the point on the PF pointed by the red arrow in Figure 1. Dotted lines witnessed the regenerated internal streams.

lyzing the topology of the points, we observe three main regions of interest: *1)* when the dimensionless freshwater flows are below 0.4, the total cost is extremely sensitive to small increase of the former; this is the result of the slow decrease of the friction losses (the flow is laminar for the values of the flowrates experienced by the IWWN) with the increase of the freshwater flow – the pipe diameters increase discretely, taking only standardized values – the sudden jumps in the PF correspond to such discrete changes in diameters; *2)* when the dimensionless freshwater flows are below 1, there are clusters of linear decrease of total cost with the increase of freshwater flow; each cluster corresponds to a change in diameter, while in each cluster there is a linear decrease of the friction losses which decreases the operating costs only – the investment part remains the same, since the pipes' diameters do not change; *3)* the last region, which is of no interest, corresponds to dimensionless freshwater flows higher than unity, meaning that the freshwater consumption exceeds the maximum value needed in the absence of optimization, which obviously is unacceptable.

Analyzing the topology presented in Figure 2, we observe some interesting perspectives in network's optimization revealed by the presence of the RU. WU6, the unit that releases the most contaminated wastewater is placed on the second position and its entire outlet flow is sent to the RU. After exiting this partial treatment, the stream's outlet contaminant concentrations match the inlet concentration of the next WUs in sequence and thus, it is completely reused. The same option for regeneration is assigned to the WU with a less contaminated water outlet, WU5, but just for the flow corresponding to the requirements of the next WUs in sequence. The last WUs are the ones which discharge the least contaminated outlet flows (Table 1) and the option assigned by the algorithm is end-pipe decontamination inside the TUs. There are four WUs that need to be supplied with freshwater, while the remaining two WUs are supplied with partially decontaminated water together with water streams coming from the previous units.

For the previously presented topology the optimal diameter of each pipe of the network

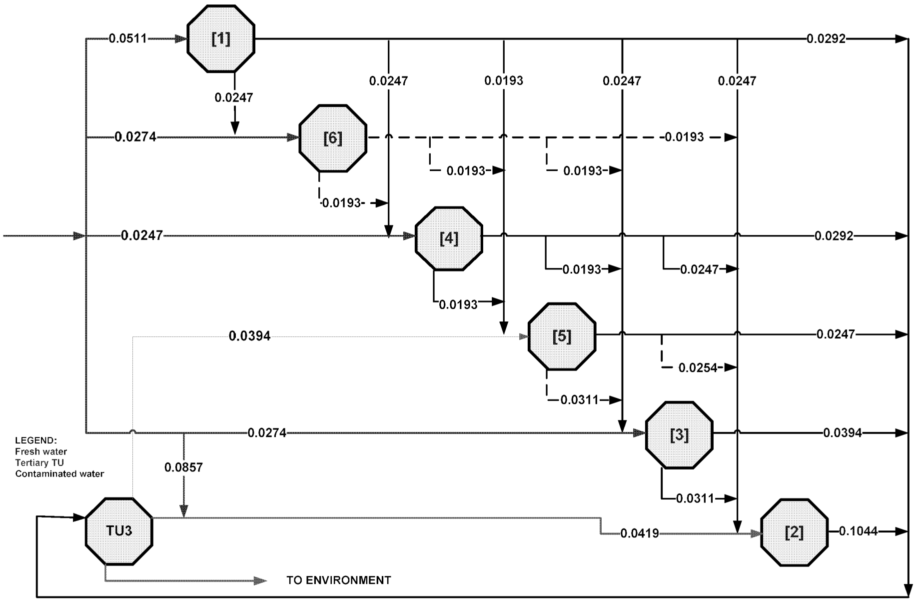

Figure 3:. The optimal standardized diameters [m] of the active pipes of the IWWN corresponding to the network presented in Figure 2.

was computed (the results being presented in Figure 3) such that to minimize the friction losses due to the fluid velocity and, thus, the investment and operating cost. The distribution of the internal diameters shows that the internal wastewater reuse is rather equilibrate, due to the use of RU as well, which implies pipes from 0.0311 m down to 0.0193 m. It is worth mentioning that WU2 has, in fact, two feeding pipes: one with freshwater with a diameter of 0.0857 m, and one with partially treated water from TU3, with a diameter of 0.0419 m, and not one common feed as depicted in Figure 3, to simplify its reading.

5. Conclusions

The dual-objective optimization of an IWWN with local regeneration possibility is studied in this paper. Local regeneration of the critical contaminants (as resulted from the computation of the mean availability indices – not shown) proves to be a better alternative to their complete decontamination in order to obtain the best network topology that observes both objective functions. The mathematical model is solved using Genetic Algorithms, minimizing concomitantly the fresh water consumption and the investment and operating costs, which ultimately is related to the energy savings possibilities. Due to the dichotomic nature of these two objective functions, freshwater consumption and total cost of the active pipes, a PF with equally optimal solutions was obtained.

The presence of the RU ensures a better wastewater reuse, equilibrating the network with respect to the internal flows; now, there is no WU lacking internal wastewater reused from predecessor WUs as is or through this RU.

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References

Foo D. C. Y., 2009, State-of-the-art review of pinch analysis techniques for water network synthesis, Industrial and Engineering Chemistry Research, 48, 5125-5159

Iancu P., Plesu V. and Lavric V., 2009, Regeneration of internal streams as an effective tool for wastewater network optimisation, Comput. Chem. Eng, 33(3), 731-742

Koppol A., Bagajewicz M., Dericks B. and Savelski M., 2003, On zero discharge solutions in the process industry, Advances in Environmental Research, 8, 151-171

Lavric V., Iancu P., Plesu V., Ivanescu I. and Ilie M., 2005, Cost-based water network optimization by genetic algorithm, Chemical Engineering Transactions, 7, 755-760

Tudor, R. and Lavric, V., 2010a, Optimization of Total Networks of Water-Using and Treatment Units by Genetic Algorithms, Ind. Eng. Chem. Res., 49, 3715-3731

Tudor, R. and Lavric, V., 2010b, Optimization of Overall Network of Water-Using and Treatment Units, Computer Aided Chemical Engineering. Elsevier 28, 913-918