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Water and Wastewater Network Retrofit through Regeneration by Critical Component Analysis

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Retrofitting a water and wastewater network is not a trivial task since this has to be done under two major supplemental constraints: geographic and/or operational. The former implies that the network topology is stiffed (the geographic position of the water sources, the contamination and the treatment units are given), the only allowed changes being the suppression or addition of some interconnections to achieve a desired goal such as furthermore minimisation of the supply water input, among others. The latter involves all the internal flows which should be kept at a given value, due to various technological constraints. The aim of the paper is to discuss the retrofit of an existing water and wastewater network satisfying two criteria: minimisation of the supply water flow using the regeneration of some designated components, as resulted from the Critical Component Analysis and a network structure as simple as possible, described by its topological index. These new topology and/or network performance are compared against the original case with respect to the topological index, mean availability and internal reuse quotient. The optimization is carried out using an improved Genetic Algorithm variant, which uses the aforementioned criteria. The solving method is well documented elsewhere (Lavric et al., 2005).

1. Retrofitting and the Zero Discharge Concept

The water and wastewater network life cycle should undertake, normally, two essential stages: design and retrofit, respectively. The retrofit or revamp appears after the water and wastewater complex comes in use and represents the modifications, which can or has to be done, in order to adjust it to the changed physical (the water supply diminished or became fluctuant), technological (better equipments with respect to the mass transfer or treatment capacity), legislative (harder constraints affecting the discharged water) and/or market (increased energy or labour costs) conditions. During retrofit, the connections between processes can be reconfigured and new equipments (like pumps) can be added. In a comprehensive review, Bagajewicz (2000) outlined different graphical and mathematical programming techniques used to design and retrofit water networks, presenting some refinery case studies for one and/or multiple contaminants. The concept of zero discharge is introduced: water is seen as an internal carrier, working in a closed circuit, such that water disposal is eliminated altogether. The only water supplied is to compensate the losses due to the units leak and chemical or biological wastes removal (see Figure 1 for details).

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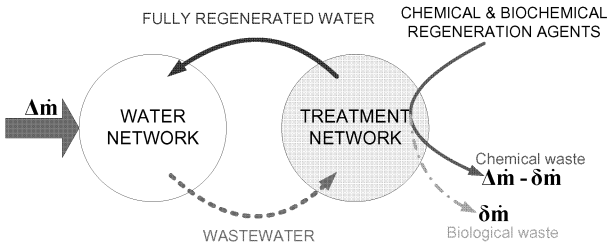

Figure 1. The concept of zero discharge

But the problem of pollutants disposal remains (the original $\Delta\dot{m}$ contaminants flow rate should be disposed of, either as chemical or biological wastes), although the redistribution of the treatment network proves to be beneficial. There are always trade-offs in retrofit problems between freshwater and wastewater treatment costs, piping costs and environmental constraints on the discharge water, applicable when the optimal use of existing capital is searched (Tan and Cruz, 2004; Alva-Argaez et al, 2006; Zheng et al., 2006). The main advantage of the zero discharge concept is the reduction of the treatment costs, since less water should be fully treated to be returned as fresh supply (Koppol and Bagajewicz, 2003; Iancu et al., 2007). Savelski and Bagajewicz (2001) showed that the concept of zero discharge is feasible only if regeneration has a sufficiently small outlet concentration (see, also, Iancu et al., 2007). Otherwise, reuse might exist, but water discharge is not completely eliminated. The main drawbacks of the zero discharge concept are the increase in the operating costs due to the supplemental pumping through the regeneration units, or in the capital cost in retrofit projects due to large scale restructuring of piping, in one hand, and the arrangement of the disposal of the solid waste generated, in the other (Koppol and Bagajewicz, 2003). The Sustainable Process Index can be used as a measure of the environmental impact, helping to retrofit a water network to achieve the minimum amount of water discharge. However, in some cases retrofitting the water network adding new pumps and pipes could increase the consumed energy to such an extent that the environmental cost gets even higher (Ku-Pineda and Tan, 2005). Although the regeneration was seen as a key technique in the retrofit stage, it is used more and more as an important component of a design process implying three steps: first, a deterministic optimization model for the network configuration with minimum freshwater use and optimal wastewater reuse and regeneration-reuse is applied – this could imply the minimization of two criteria: freshwater consumption and infrastructure costs (Mariano-Romero et al, 2006); then, a sensitivity analysis is done, in which uncertainty is introduced as maximum and minimum ranges in operating conditions. Finally, a stochastic approach is used to extend the analysis, based on the two-stage recourse problem method with finite number of realization (Al-Redhwan et al., 2005).

2. Pre-retrofit Analysis – useful concepts

Mean Availability. In the process of water network analysis, the concept of *unit availability*, defined as the mean of the mass transfer driving forces at the entrance and exit of the unit, permits the identification of each bottlenecking unit together with the contaminant responsible for it. Obviously, a unit having zero or very low availability for a contaminant becomes stiffed with respect to the carrier. Taking the arithmetic mean of all units, the mean availability is computed, which will have specific values for each contaminant.

Critical Contaminant – applies to the whole network, identifying the contaminant with the lowest mean availability. This contaminant determines either the supply water consumption or part of the internal reuse, due to mass transfer bottlenecking. It attains a threshold concentration starting with the early stages, which prevents a deeper internal reuse of water. This contaminant should be the primary target for partial regeneration.

Bottleneck Island groups the critical contaminant and its eventual neighbours, isolated from the rest of contaminants, who have larger mean availabilities. The regeneration of any single contaminant from a bottleneck island does not guarantee a better retrofitted network, but the regeneration of all the contaminants of the island does.

Topological Index is defined as the ratio between the active internal pipes' length (the ducts through which the reused water actually flows between units) and the overall active tubes' length (the former plus the length of the ducts through which water actually flows from the supply sources to the network and from the network to the treatment). A rather low topological index could mean a scarce internal water reuse or a full connection of the all units to the supply sources and treatment. A higher topological index could mean an improvement of the internal water reuse or a reduction of the number of units directly supplied from the water sources or directly sending the contaminated water to the treatment.

Internal/External Reuse Quotient (I/ERQ) is the ratio between the flow of the reused internal/external water and the flow of the contaminated water sent to treatment or recycled back, in zero discharge case. The higher the internal/external reuse quotient is, the easier the task of the treatment units should be, thus decreasing its operating costs together with the environmental impact of the discharged water.

Partial regeneration is defined as the removal of some designated contaminants from an internal flow down to an acceptable level, once their concentration pass over an imposed threshold. The regeneration boundaries should be subject of an economic analysis, especially the outlet concentrations, whose values could be optimized. When this is not possible, the regenerated water should match the minimum non-zero allowable input restrictions for all units. The same criterion should be applied to where regeneration should start, but this time considering the output restrictions (Iancu et al., 2007). The regeneration would happen more often, leading to an overall increase in the mass transfer driving force at the network level; this will diminish the supply water demand.

3. Mathematical Model and Retrofit Strategy

A complete description of the mathematical model and the solving strategy is given in (Lavric et al., 2005). The retrofit could be done using either the same criterion as in the design stage, or using other criteria, considered more appropriate. For example, the design of the network could have been done using the supply water as the minimization criterion, while the retrofit could use beside this the criterion of the minimum length of the active pipes in the network. Anyway, the retrofit implies internal water regeneration, which could be partial, targeting only the critical contaminants from the bottleneck island set, or total, corresponding to the zero discharge concept.

4. Results and Discussions

The case study chosen for the retrofit analysis is a synthetic water network with one source supplying fresh water, seven units and four contaminants (not presented here).

Table 1. Base case design/regeneration retrofit for a synthetic water network with one source with fresh water, seven units and four contaminants

Criterion	Case	Reordering by	Flow under one t/hr	Supply Water, t/hr	IRQ	Regenerated IRQ ***ERQ***	Regenerated Recycled Water, t/hr	Topological Index, -	Component Availability, ppm				Overall exit contaminant concentration, ppm			
									1	2	3	4	1	2	3	4
Supply Water	A	F	Allow	49.657	0.192	NA	NA	0.3610	36.1	*14.77*	**12.87**	47.43	33.51	43.64	50.75	24.47
			Neglect	48.624	0.178	NA	NA	0.1327	35.61	*14.75*	**14.73**	47.27	34.22	44.57	51.83	24.99
		L	Allow	43.712	0.409	NA	NA	0.3747	37.18	*14.69*	**12.13**	47.26	38.07	48.58	57.65	27.80
			Neglect	42.531	0.309	NA	NA	0.1596	37.02	*14.98*	**14.13**	46.47	39.12	50.95	59.25	28.57
	B	F	Allow	43.452	0.0	0.381	NA	0.3842	32.26	**9.94**	38.03	44.06	38.30	49.87	16.17	27.96
			Neglect	44.301	0.0	0.274	NA	0.1883	33.57	**9.98**	38.07	46.87	37.56	48.92	15.76	27.43
		L	Allow	37.449	0.0	0.499	NA	0.4440	33.99	**11.08**	35.35	45.02	44.43	57.87	23.47	32.44
			Neglect	36.718	0.0	0.550	NA	0.2437	34.15	**9.2**	35.15	44.11	45.32	59.02	22.98	33.09
	C	F	Allow	49.598	0.136	0.216	NA	0.3332	36.70	28.83	**12.23**	48.04	33.55	25.47	50.81	24.50
			Neglect	47.969	0.035	0.151	NA	0.1157	35.59	33.46	**14.60**	47.31	34.69	14.71	52.53	25.33
		L	Allow	43.614	0.316	0.132	NA	0.3747	37.16	29.99	**12.08**	47.46	38.15	24.63	57.78	27.86
			Neglect	42.985	0.258	0.003	NA	0.2521	37.24	31.23	**13.35**	47.15	38.71	17.38	58.63	28.27
	D	F	Allow	39.698	0.009	0.670	NA	0.3964	31.82	33.02	35.70	43.74	41.92	17.54	23.93	30.61
			Neglect	38.564	0.0	0.501	NA	0.2302	32.02	33.27	36.03	42.63	43.15	18.29	24.89	31.51
		L	Allow	32.723	0.355	0.501	NA	0.4423	31.78	28.49	29.91	41.59	50.85	30.93	37.93	37.13
			Neglect	32.322	0.356	0.539	NA	0.3215	31.48	28.45	29.82	41.06	51.48	31.70	39.02	37.59
	E	F	Allow	NA	NA	***0.372***	37.183	0.6935	53.41	39.56	44.84	58.64	0.0	0.0	0.0	0.0
			Neglect	NA	NA	***0.401***	40.626	0.4824	53.38	39.52	44.77	58.61	0.0	0.0	0.0	0.0
		L	Allow	NA	NA	***0.382***	39.736	0.5950	52.58	37.66	43.22	57.48	0.0	0.0	0.0	0.0
			Neglect	NA	NA	***0.297***	45.451	0.6587	52.91	38.33	43.96	57.90	0.0	0.0	0.0	0.0

A – Base case; B – Critical component regeneration; C – Next to Critical component regeneration; D – Critical components' island regeneration; E – Zero discharge; F – units were reordered by fresh water needs; L - units were reordered by their loads; NA – Not Applicable; **Bold** - Critical component; *Italics* – Next to Critical component; **Bold** & *Italics* - Critical components' island

The complete results of the analysis are summarized in Table 1. The water network with the lowest fresh water consumption, higher internal reuse quotient and internal flows higher than one (this corresponds to the fourth line in Table 1) is depicted in Figure 2 and has been chosen as the best design variant. This water network, which will be, from now on the base case, has the simplest topology, although its topological index is next to the smallest despite the presence of only three internal reuse flows; the smallest topological index corresponds to a network with four internal reuse flows, but having the unit 2 sending water to treatment, which increases the total active pipes' length and, thus, the cost of investment.

4.1 Regeneration policy

It must be emphasized that this study was done disregarding the geographical position of the regeneration unit, thus the length of the pipes transporting the contaminated water to it and from it. The assumption was that when the exit of a unit has suitable concentrations, it enters a generic regeneration unit from which it exits with the imposed concentrations ($\min_{i=1}^{7}\left(C_{ij}^{In,\max}\right), j=1,4$). Afterwards, the flow is split to the subsequent units according to their needs.

Partial regeneration is used to retrofit the base case design, since it is cheaper than total regeneration (with zero discharge, its extreme case). With the purpose of picking-up the right species to be regenerated, a critical contaminant analysis has to be done, computing the mean availability for each component. The examination of Table 1 shows little differences between the four variants investigated for the base case discrimination, with respect to this mean availability (case A). More than that, there are two limiting components, which appear to form a bottlenecking island. In order to prove this, separate retrofit analysis were done, regenerating only one of the two contaminants (cases B and C). Although there is a decrease in the fresh water consumption, when contaminant three is regenerated separately, which is not the case for the second contaminant, the results from Table 2 show that the mean availability for the other limiting contaminant actually decreases slightly, which means that both species belong to the bottlenecking island and that further improvements could be expected. When the whole bottleneck island is subject to regeneration (case D), the fresh water consumption has an

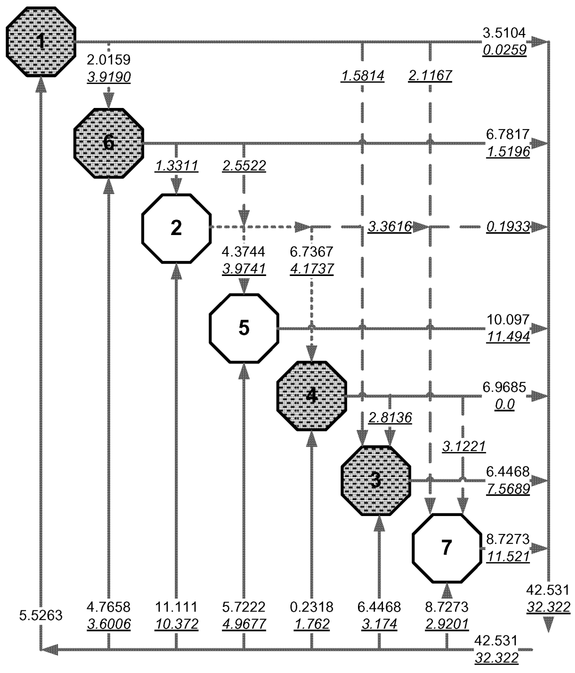

Figure 2. The base case water network; <u>*retrofitted water network*</u>, regenerating the bottlenecking island contaminants after units 1, 6, 4 and 3.

impressive drop of about 25% for all variants, while the mean availability of the two contaminants levels with the other two. For the base case under scrutiny, it is remarkable that not all the internal flows are subject to regeneration, which means smaller than expected investment (for the capacity of the regeneration unit) and operating costs. The retrofitted network is also depicted in Figure 1; the complexity of the internal structure increases, since eight new links appeared (these with *italic* underlined flows) and one disappears (the one with *0.0*).

4.1 Zero discharge policy

When zero discharge is used as criterion for retrofitting (case E), the best topology (not shown) corresponds to a water carrier flow of 40.626 t/hr, subject to regeneration down to zero contaminants' concentration; although this flow seems higher than in the partial regeneration, it should be recalled that, for the latter case, not only 32.322 t/hr of flow has to be regenerated down to level admissible for the discharge into environment, but another 17.42 t/hr are partially regenerated for the internal reuse. This gives a much higher total flow (49.742 t/hr) subject to regeneration, so the zero discharge network should be advantageous regarding at least the costs of this stage. A further improvement of the regeneration costs associated with the closed water system would be to relax the exit concentration of the regenerated water to the values used in partial regeneration.

5. Conclusions

Some useful concepts have been introduced *(unit availability, mean availability, critical contaminant, bottleneck island, topological index, internal/external reuse quotient*) which proved to be very useful in characterizing a water network, already existing or still in the design process. Based upon critical contaminant analysis, which emphasizes the existence of a bottleneck island, the contaminants subject to partial regeneration are selected, and a retrofit is proposed accordingly. A comparison against the zero discharge retrofit is done. It becomes apparent that a detailed economic analysis should be added as an outer stage in optimizing the retrofit, focusing upon nonlinear regeneration cost dependency with respect to the outlet contaminant concentrations.

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