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INFLUENCE OF REGENERATION UPON THE FRESH WATER CONSUMPTION OF WATER NETWORKS

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Această lucrare introduce o nouă abordare în domeniul optimizării rețelelor industriale de apă/apă uzată prin asocierea optimizării dublu obiectiv cu beneficiile reprezentate de oportunitățile pentru regenerare. Optimizarea dublu obiectiv ia în considerare doi dintre cei mai importanți parametrii ai rețelei de apă: consumul de apă proaspătă și costul total (cuprinzând costurile de operare și costurile de investiție). O unitate de regenerare este integrată în structura rețelei cu scopul de a evalua beneficiile sale asupra topologiei generale și, de asemenea, asupra funcțiilor obiectiv. Metodologia este aplicată pe un studiu de caz real, o rafinărie de petrol prezentată de Bagajewicz et al. [12].

This paper introduces a new approach in the field of industrial water/wastewater networks optimization by compiling the double objective optimization with the benefits of regeneration opportunities. The dual-objective optimization accounts for the most two important parameters of a water network: fresh water consumption and total cost (comprising operating and investment costs). A regeneration unit is integrated within the network in order to evaluate its benefits upon the overall topology and also upon the objective functions. The methodology is applied on a real case study,

1. Introduction

Wastewater consumption minimization has gained more attention due to the increasing concern about the environmental and economic issues associated with water usage and wastewater discharge. In chemical industry, wastewater production became a cost to take in serious account, once it is generated in different operations, such as contact between water and process materials during mass transfer operations, rejected streams from the utilities system, cleaning and hosing operations and by-products of reaction, containing several different types of contaminants in different amounts. The need to find an optimal water network (WN) and the evolution of process integration concept in the last decades brought new alternatives in the quest to reduce water consumption and wastewater production. These alternatives are:

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• *Reuse*. Wastewater from some operations can be directly used in other operations; blending and/or mixing with some fresh water may be required.
• *Regeneration recycle*. Wastewater from some operations is regenerated to remove contaminants (which would otherwise be prohibited from reuse) before it is used within the same operation.
• *Regeneration reuse*. In this third option, the regenerated water is decontaminated by partial treatment to improve its quality in order to be redirected to other operations from the network [1, 11, 12, 13]. Different types of purification techniques like filtration, activated carbon or biological treatment may be applied.

A water network with regeneration recycling can reduce fresh water consumption and wastewater discharge to the maximum extent. Moreover, if post-regeneration concentrations are low enough, the consumption of fresh water would be minimized to that of make-up, and then the closed circuit of water between water-using processes and regeneration units (RUs) can meet the usage demand of the system.

The methodologies to synthesise a WN can be broadly classified into two general categories: the insight-based graphical pinch analysis [2] and the mathematical-based optimisation techniques [1, 8, 11, 12, 13]. The main advantage of graphical pinch analysis technique is that, the various water network targets (such as fresh water and wastewater flow rates and pinch location) are identified before the detailed network design. However, this technique is often limited to single-component systems. It also becomes cumbersome as the number of streams and units increases. Additionally, the graphical techniques' major drawback is given by their inability to provide rigorous solutions to multiple contaminant problems [2]. On the other hand, mathematical-based optimisation methods serve as a good synthesis tool in handling more complex systems, such as multiple contaminant networks, complex water-using processes and more elaborate objective functions (fresh water consumption, cost, number of connections, etc.) [1, 3, 4, 5, 6].

The first complex mathematical optimization including regeneration was introduced by Takama *et al.* [7] who addressed the problem of optimal water allocation in a petroleum refinery based on a superstructure of all possible re-use and regeneration opportunities. Economic benefits are undoubtedly the driven force for the industry to implement wastewater reuse programs, thus most attempts have focused on the economic optimization of water systems. The total cost is taken as an objective in many network optimization approaches [3, 4, 6, 8]. However, when minimizing the total cost, many design parameters, such as the distances between different processes and the type of regeneration equipment, should be specified. Furthermore, several expressions are given for the estimation of each kind of cost, most of them root in some experimental and simple hypothesis, and therefore the regeneration cost is only correlated to the regenerated water flow rate. Fresh water consumption, regenerated water flow rate and contaminant regeneration load are three important parameters for a regeneration recycling water system, which all have an impact on the total cost of the system. Therefore, the optimization for regeneration recycling WN is basically a multi-objective problem. Koppol et al. [6] presented a mathematical model which allows the analysis of the effect of varying the regeneration concentration upon the amounts of fresh water consumed and wastewater regenerated, and the total costs. Four industrial examples are discussed.

Feng et al. [9] formulated, based on the superstructure of regeneration recycling system, the multi-objective problem which was afterwards converted into several sequential mathematical models with single objective. According to the relative importance of the goals, fresh water consumption, regenerated water flow rate and contaminant regeneration load were minimized step by step. The approach exempts considering the complex and variable economic factors, and only takes those basic parameters of a water system into account, thus simplifying the optimizing procedure. Also the results were economically favourable in terms of qualitative analysis.

Lavric et al. [10] considered the availability of multiple supply water sources which have different level of pollutants contamination. A cost-based optimization criterion was used to identify the optimum water network topology which reduces both the investment (piping network cost, built using the optimum pipes' diameter) and operating (pumping) costs, when water sources with or without multiple contaminants are used together.

Wastewater RUs are generally modelled as units that remove a certain quantity of pollutant from a single stream of contaminated water; the regenerators thus discharges a single stream of partially purified water for further reuse and recycle. The RU can have, generally, fixed outlet contaminant concentrations or fixed ratios of the outlet and inlet contaminant concentrations.

The problem of multi-objective optimization of WN with multiple contaminants has been analysed in few studies [4, 5, 9, 13, 15, 16]. Feng et al. [9] have proposed a sequential multi-objective optimization for the optimization of regeneration recycling WN. The three important parameters with impact upon the total cost of the system employed in their study were: fresh water consumption, regenerated flow rate and contaminant regeneration load. Therefore, they have developed a methodology for the multi-objective optimization of such systems by converting it into several sequential mathematical models with single objective. Although, their approach exempts considering the number of interconnections or any economic factor, they conclude that the results obtained were economically favourable in terms of qualitative analysis [9]. Another study [13] uses a similar approach, employing a multi-objective approach with three objective functions (the fresh water flow rate at the network entrance, the water flow-rate at inlet of regeneration units and the number of interconnections into the network). Similar to the previous study, the economical insights is indirectly considered within the second objective function (n.r. the water flow rate at inlet of regeneration units) as a high amount of regenerated water corresponds to an increased cost of regeneration. The MINLP procedure developed by them provides a set of equally optimal solutions in the form of Pareto fronts. The problem of selecting a good particular solution from the set is solved by applying two procedures (TOPSIS vs. GEC).

In this paper we analyse the problem of multi-objective optimization of the water/wastewater networks which benefit from regeneration opportunities. A regeneration unit is integrated within the network in order to evaluate its benefits upon the overall topology and also upon the objective functions. The methodology has been applied on a real case study, a petroleum refinery presented by Bagajewicz et al. [12]

The regeneration option is used as fine tuning tool for the evaluation of the impact/benefits upon the objective functions employed. The multi-objective optimization considers the fresh water consumption (FWC) at the same time with total cost (TC) (based on both investment and operating costs) minimization. In this manner, the set of equally optimal solutions in the form of the Pareto Front (PF) is obtained. The methodology is applied on a real case study presented by Bagajewicz et al. [12] for which several scenarios are described and the results are compared to each other.

2. Mathematical model

A WN is a set of water-using units (WUs), one fresh water source, one regeneration unit and internal wastewater streams linking them. In order to ensure driving force equipartition along the process a WN can be seen as an oriented graph in which the WUs are ordered according to their fresh water consumption starting with the water-using units with the most restrictive inlet constraints. Any WU can receive streams from the WUs preceding and also regenerated water as long as the inlet restrictions are observed (Fig. 1).

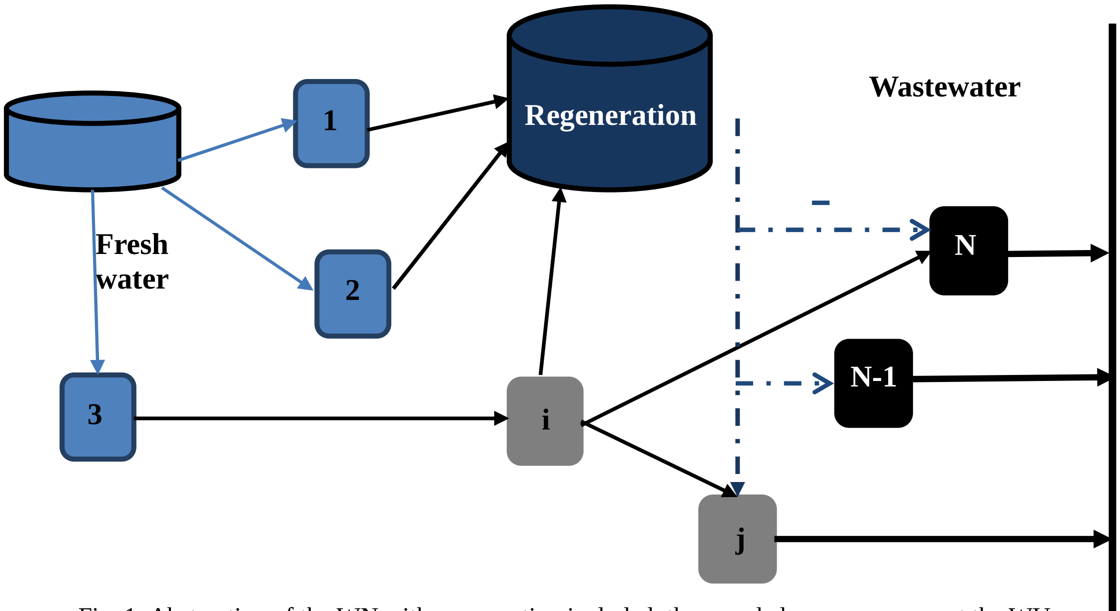
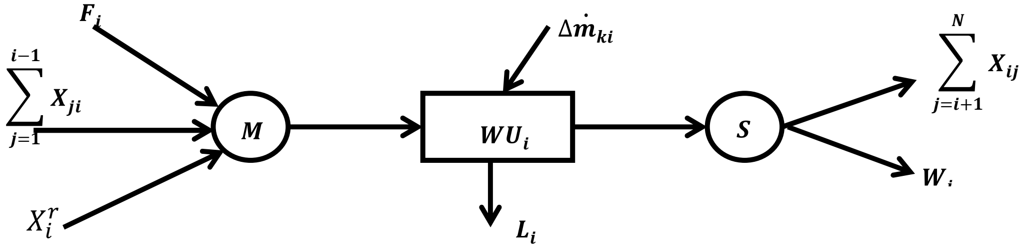


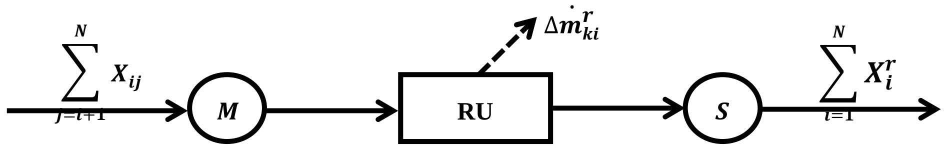
Fig. 1. Abstraction of the WN with regeneration included: the rounded squares represent the WUs, the arrows connecting them are the pipes transporting the water reused internally (the continues arrows represent the fresh/wastewater while the dashed arrows stand for the regenerated flows), one fresh water source and one regeneration unit (RU) able to decontaminate the wastewater up a certain level. The WUs are grouped into clusters: first cluster is formed from the WUs with inlet contaminant-free units (units denoted in the caption by 1, 2 and 3), next cluster is formed by the units having moderately inlet restrictions (units denoted in the caption by *i* and *j*) while last cluster is composed of the units with the most relaxed inlet restrictions thus having the most contaminated streams (units denoted in the figure by *N-1* and *N*)

The regeneration unit receives internal wastewater streams with high contaminant concentration. By specific processes the concentration of one, two or several contaminants is reduced to a certain level. The algorithm includes the possibility of modelling the RU with respect to the concentration of the contaminant removed: either as having fixed output concentration (FO) or as fixed ratio (FR) contaminant removal.

The complete description of the abstraction of the water/wastewater network together with the mathematical model of the WN can be found in Lavric et al. [11] and Iancu et al. [1]. In what follows a brief mathematical model of a WN endowed with a RU is given and then we will focus on the multi-objective optimization of the WN with regeneration option included.



a.



b.

Fig. 2. a. The generic WUs abstraction: one mixing unit at the inlet of each WUs and similarly one splitting unit at the outlet, F_i represents the fresh water inflow, $\sum_{j=1}^{i-1} X_{ji}$ - the water flow coming from unit j and heading to unit i, X_i^r - the regenerated water flow assigned to unit i; the outlet flow is divided into flows reused the next WUs in sequence ($\sum_{j=i+1}^{N} X_{ij}$) and the wastewater flow sent to the treatment section (W_i), $\Delta\dot{m}_{ki}$ represents the load of contaminants accumulated in each WUs b. The generic RU abstraction: at inlet the water flows ($\sum_{j=i+1}^{N} X_{ij}$) coming from the WUs of the network are mixed before entering the RU, the outlet flow is divided into flows ($\sum_{i=1}^{N} X_i^r$) further used by WUs, $\Delta\dot{m}_{ki}^r$ represents the load of contaminants removed within the RU. Two modelling possibilities have been accounted for the RU: fixed ratio and fixed outlet.

The mathematical model for the WUs graph is:

Total mass balance:

$$F_i + \sum_{j=1}^{i-1} X_{ji} + X_i^r + \sum_{k=1}^{K} \Delta\dot{m}_{ki} = \sum_{j=i+1}^{N} X_{ij} + W_i + L_i \tag{1}$$

Partial mass balance for the contaminant k:

$$F_i + \sum_{j=1}^{i-1} X_{ji} C_{kj}^{WU,out} + X_i^r C_k^{r,out} + \Delta\dot{m}_{ki} = \left(\sum_{j=i+1}^{N} X_{ij} + W_i + L_i \right) C_{ki}^{WU,out} \tag{2}$$

Constraints

– inlet WUs concentrations:

$$C_{ki}^{WU,in} = \frac{F_i + \sum_{j=1}^{i-1} X_{ji} C_{kj}^{WU,out} + X_i^r C_{kt}^{r,out}}{F_i + \sum_{j=1}^{i-1} X_{ji} + X_i^r} \le C_{ki}^{WU,in,\max} \tag{3}$$

– outlet WUs concentrations:

$$C_{ki}^{WU,out} = \frac{F_i + \sum_{j=1}^{i-1} X_{ji} C_{kj}^{WU,out} + X_i^r C_{kt}^{TU,out} + \Delta \dot{m}_{ki}}{\sum_{j=i+1}^{N} X_{ij} + W_{it} + L_i} \leq C_{ki}^{WU,out,\max} \quad (4)$$

The mathematical model for the RU is:

Total mass balance:

$$\sum_{j=i+1}^{N} X_{ij} = \sum_{k=1}^{K} \Delta \dot{m}_{ki}^r + \sum_{i=1}^{N} X_i^r \quad (5)$$

Partial mass balance for the contaminant k:

$$\sum_{j=i+1}^{N} X_{ij} C_{ki}^{WU,out} = \Delta \dot{m}_{ki}^r + \sum_{i=1}^{N} X_i^r C_k^{r,out} \quad (6)$$

2.1. Deriving of the vector objective function

The optimality of a WN can be sought in various ways, each optimal solution corresponding to a different topology. Considering the optimality of a WN only with respect to fresh water consumption may hinder some higher cost, related for example to fresh water price, fresh water availability or operating costs. Therefore, the dual objective function employed in this study accounts for the fresh consumption while the other describes the total cost. The objective function related to costs comprises both investment costs and operating charges.

The fresh water consumption as objective function is obtained from the condition that each fresh water stream fed to WU i should guarantee the observation at the same time of both inlet and outlet restriction with respect to the pollutant concentrations:

$$\Phi = \frac{\sum_{i=1}^{N} \left\{ \max \left[\max_k \left(F_{ki}^{in} \right), \max_k \left(F_{ki}^{out} \right) \right] \right\}}{F^{\max}} \quad (7)$$

In equation (7), F_{ki}^{in} represents the fresh water flow observing the inlet restriction for the pollutant k, while F_{ki}^{out} represents the fresh water flow observing the outlet restriction for the pollutant k. Choosing the maximum of both maxima ensures the observation of all restrictions, both at inlet and at outlet, for WU_i. The denominator represents the sum of the fresh water flows which should feed all WUs in the absence of any internal reuse.

The second element of this dual-objective function is the total cost of the active pipe system, depending on the costs of the unit length of a pipe linking two consecutive WUs and having the optimum economic diameter, and it was thoroughly presented in Lavric et al. [10]:

$$C_{ij}^{*} = \left([C^{*}]_{pumping} + [C^{*}]_{pipe}\right)_{ij} =$$

$$= \left[\frac{\chi \cdot q_{ij}^{a} \cdot \rho^{\beta} \cdot \mu^{\gamma} \cdot K \cdot (1+J) \cdot H_{y}}{D_{ij}^{\delta}} + B'\right]_{pumping} + \left[\left(1+F\right) \cdot X \cdot \left(\frac{D_{ij}}{D_{r}}\right) \cdot K_{F}\right]_{pipe} \tag{8}$$

Equation (8) has been derived considering one year as the time basis, the exponents of the pumping term depend upon the flow regime and the Fanning friction factor value, D_{ij} stands for the optimum economic diameter of the pipe linking the units i and j, while D_{r} is the reference diameter. The flow regime gives the formula to compute D_{ij} :

$$turbulent\ flow:\ D_{ij} = \left[\frac{6.04 \cdot 10^{-4} D_{r}^{n} \cdot q_{ij}^{2.84} \cdot \rho^{0.84} \cdot \mu_{c}^{0.16} \cdot K \cdot \left(1+J\right) \cdot H_{y}}{n \cdot \left(1+F\right) \cdot X \cdot E \cdot K_{F}}\right]^{\frac{1}{4.84+n}} \tag{9}$$

$$laminar\ flow:\ D_{ij} = \left[\frac{0.1628 \cdot D_{r}^{n} \cdot q_{ij}^{2} \cdot \mu_{c} \cdot K \cdot \left(1+J\right) \cdot H_{y}}{n \cdot \left(1+F\right) \cdot X \cdot E \cdot K_{F}}\right]^{\frac{1}{4+n}} \tag{10}$$

The total cost of the active pipe system is given by the topology of the network, which is represented by the network of the active pipes (non-zero outlet flows):

$$\Gamma = \frac{\underbrace{\underbrace{\sum_{j=1}^{N} C_{0,j}^{*} \cdot l_{0,j}^{*}}_{\text{supply pipes}} + \underbrace{\sum_{i=1}^{N} \sum_{j=i+1}^{N} C_{i,j}^{*} \cdot l_{i,j}^{*}}_{\text{internal pipes}}}_{\text{active}}}{\underbrace{\sum_{j=1}^{N} C_{0,j}^{*} \cdot l_{0,j} + \sum_{i=1}^{N} \sum_{j=i+1}^{N} C_{i,j}^{*} \cdot l_{i,j}}_{\text{overall}}} \tag{11}$$

It should be specified that the denominator in equation (11) is computed using the largest diameter value as resulted from applying (8) with the highest fresh water inflow for all the pipes of the WN, regardless if they are active or virtual (their presence is not necessary, since no water will flow through them). This ensures lower than unity values for the dimensionless total cost of the active pipes even when all the pipes of the grid are active, but for sure the flows will be lower than this highest value. The costs related to the regeneration unit were not taken into account.

The dimensionless dual-objective function is obtained considering the vector whose components are the fresh water consumption, (7), and total cost of the active pipes, (11):

$$fob = \begin{Bmatrix} \Phi \\ \Gamma \end{Bmatrix} \tag{12}$$

Finding the minimum of this dual-objective function is not simple since the complete model is fully non-linear. We chose as optimization tool the genetic algorithm as implemented in Matlab® (MathWorks®, MA) as the function "*gamultiobj*".

3. Case study

We have applied the previously described algorithm on a real case study, n.r. a petroleum refinery, presented by Bagajewicz et al. [12]. In petroleum refining water is mainly used to wash inorganics from hydrocarbons. Together with inorganics, water also accumulates organic contaminants like oil, grease, phenols, cresols, xylenols, etc.

Table 1

Inlet and outlet restrictions of the water-using units of the network (Bagajewicz et al. [12])

WU no.	$C^{in,\max}$ (ppm)				$C^{out,\max}$ (ppm)			
	C_1	C_2	C_3	C_4	C_1	C_2	C_3	C_4
WU_1	300	50	5000	1500	500	500	11000	300
WU_2	10	1	0	0	200	4000	500	1000
WU_3	10	1	0	0	1000	3500	2000	3500
WU_4	100	200	50	1000	400	6000	2000	3500
WU_5	100	200	50	1000	350	6000	1800	3500
WU_6	85	200	300	200	350	1800	6500	1000
WU_7	1000	1000	150	200	9500	6500	450	400
WU_8	800	1200	150	200	9500	6500	450	400

Some processes use steam as a stripping medium in distillation and as a driving fluid in vacuum ejectors. In this case study, the contaminants in wastewater were broadly classified into four categories: *salts* (denoted by C_1), *organics* (denoted by C_2), *hydrogen sulphide* (denoted by C_3) and *ammonia* (denoted by C_4).

Table 2

Mass load of contaminants (Bagajewicz et al. [12])

Mass load of contaminants, $\Delta\dot{m}_{ki}$(g/hr)	Water-using units							
	WU_1	WU_2	WU_3	WU_4	WU_5	WU_6	WU_7	WU_8
C_1	180	3610	600	2000	3000	3800	120000	140000
C_2	1200	100000	30000	60000	75000	45000	480000	220000
C_3	750	250	1500	800	1900	1100	1500	1200
C_4	100	800	1000	1000	2100	2000	0	0

The case study involves eight WUs denoted as follows: WU_1 - Caustic treating, WU_2 – Distillation, WU_3 – Amine sweeting, WU_4 – Sweetening (Merox I), WU_5 – Sweetening (Merox II), WU_6 – Hydrotreating, WU_7 – Desalter I and WU_8 – Desalter II. The load of contaminants accumulated in each WU together with the limiting inlet and outlet concentration are presented in Table 1 and Table 2. In Table 3 are listed the distances (in meters) between the fresh water source and WUs and also among the processes.

Table 3

Distances between the WUs in the water and wastewater network (m), Bagajewicz et al. [12]

Units	Water-using units							
	WU_1	WU_2	WU_3	WU_4	WU_5	WU_6	WU_7	WU_8
Fresh water source	365.76	457.20	274.32	640.08	731.52	182.88	91.44	182.88
WU_1		365.76	182.88	274.32	365.76	182.88	274.32	365.76
WU_2			274.32	274.32	365.76	365.76	274.32	182.88
WU_3				365.76	457.20	91.44	182.88	91.44
WU_4					91.44	457.20	548.64	457.20
WU_5						548.64	640.08	548.64
WU_6							91.44	182.88
WU_7								91.44

The first step in designing a WN with regeneration option included is to rank the WUs according to a ranking criterion [1, 4, 11, 14]. In this study we have used one ranking criteria, namely fresh water consumption (FWC) [11]. The meaning of this criterion is that it ranks the WUs according to the maximum fresh water flow feeding each one of them such that to observe all restriction, both at inlet and outlet, in the absence of any internal wastewater reuse. It must be pointed out that ranking the WUs does not introduce some new restrictions in the network topology, but merely helps keeping the driving force of the mass transfer as evenly distributed as possible [4].

Independently on the ranking criterion, the inlet-contaminant free WUs will always be placed first since, due to their inlet restrictions, they cannot be fed with internally reused wastewater.

4. Results and discussions

The algorithm for the dual-objective optimization of a WN, as described in Tudor and Lavric [4], has been applied on the aforementioned case study. Several scenarios were run to observe how the optimal topology of the network is influenced by the presence of the RU and which the variations in terms of *fresh water inflow* and *total wastewater outflow* are.

The first three scenarios are the base-cases in which the regeneration option is not included, the optimization being done with respect to: a) FWC only; b) TC only, and c) both FWC and TC, as parts of a dual-objective function. All other scenarios refer to the dual-objective optimization of the WN in which the regeneration option is included. We have observed that the fresh water flow has a considerably higher value when the optimization was done with respect to the TC only, since its cost is not included in the components of the TC function. This was due to the fact that when costs are the only objective the optimization algorithm assigns higher flows for the active pipes which means lower friction thus shifting the flow from laminar towards turbulent in order to minimize the costs. On the other hand, although higher, the fresh water flows have very close values for the dual-objective optimization vs. FWC as single criterion (Table 4 – Scenarios 1 and 3). The PF corresponding to the dual-objective optimization of the WN in the absence of regeneration (Scenario 3) is presented in Fig. 3. We have observed that the optimal solutions are grouped around several regions, basically for each region there is a minor change in the fresh water flow which corresponds to a variation of the TC over a relatively large interval. This is partly due to the fact that the pipes connecting the WUs have standardized diameters. Therefore the optimum diameter for a particular value of one water flow shifts to the next standardized value, this new value being maintained for a certain range of flows, the highest value of the flow corresponding to the lower value of the TC over one range.

In order to measure how close to optimality each resulted WN is, for each base-case scenarios we have computed the *mean availability* of each WU for all the contaminants.

The notion of *mean availability* (MA) has been introduced by Iancu et al. [1] and refers to the mean remaining driving force over the WN, computed using the concentration differences at the inlet and at the outlet of each WU, between the actual state of the WU and its constraints. A close to zero value of the MA for the contaminant k of the WU_i indicates that it works near optimality; i.e., any change in the flow circulating through it having as result either a violation of the output restrictions (when the flow decreases) or a departure from the optimality (when the flow increases). On the other hand, a high value for MA (computed for each contaminant) reveals that the unit can function with lower water flows. The ideal WN is represented by zero value of MA of all contaminants of the system. In table 4 are presented the values of the regenerated water flows while in Table 6 are presented the values of overall MA, obtained as the mean of the individual MA of each contaminant in each WU.

Based on the results obtained for MA, two important indices have been derived [1]:

- the *critical contaminant* of the system: has the lowest value of MA and therefore is the one that determines the supply water consumption.
- the *bottleneck island*: a group of contaminants having close value of MA which are also highly different from the others (the critical contaminant is generally included).

From the MA values for the three base-cases we have drown the conclusion that the critical contaminant of the system is C_2 which gives the lowest MAs for all WUs (Table 6 – Scenario 1, 2 and 3).

When optimizing the WN with regeneration included, the dual-objective function gives a set of equally optimal solutions. Therefore, for each scenario with regeneration included we have chosen from the Pareto front, the solution corresponding to the lowest fresh water inflow. This choice was due to the fact that we were more interested in the fresh water consumption than in the costs of the WN. Regardless of our choice, one can select the point from the PF corresponding to the lowest value of the TC. As long as all solutions from the PF are equally optimal, one can select any of the points based on an additional criteria: for example, for a WN placed in a region with fresh water scarcity the point of interest would be the one with the lowest value for the fresh water flow; similarly, in cases where the energy supplies are poor or very expensive the point of interest is represented by the set with the lowest value of the TC. Several scenarios were constructed, the description of each of them and the results obtained is represented in Table 4. For each scenario both types of regeneration were analysed: fixed ratio (FR) or fixed outlet (FO); the regeneration limits are presented in Table 5.

Table 4

Scenarios of the optimized WN with/without regeneration integrated

Scenario	Objective function	Regenerated contaminant	Total Regenerated flow (t/h)	Regeneration type	Total fresh water inflow (t/h)	Total wastewater outflow (t/h)
1	FWC	-	-	-	170.49	171.79
2	TC	-	-	-	362.49	363.79
3	FWC & TC	-	-	-	171.89	173.19
4	FWC & TC	C2	59.56	FO	129.28	130.582
5	FWC & TC	C2	60.03	FR	134.05	135.35
6	FWC & TC	C1	11.62	FO	172.14	173.44
7	FWC & TC	C1	11.50	FR	173.23	174.53
8	FWC & TC	C3 & C4	0	FO	176.05	177.35
9	FWC & TC	C3 &C4	0	FR	176.05	177.35
10	FWC & TC	C1 & C3	0	FO	174.19	175.49
11	FWC & TC	C1 & C3	0	FR	176.05	177.35
12	FWC & TC	C3	0	FO	171.88	173.18
13	FWC & TC	C3	0	FR	178.90	180.20
14	FWC & TC	C1 & C4	0	FO	179.63	180.9
15	FWC & TC	C1 & C4	0	FR	174.59	175.89
16	FWC & TC	C1, C2 & C4	0	FO	173.24	174.54
17	FWC & TC	C1, C2 & C4	0	FR	176.05	177.35

Table 5

Regeneration limits of the both types of regeneration models employed in the study

Contaminant	*Regeneration limits*	
	FR	*FO (ppm)*
C1	*0.9*	8.5
C2		5
C3		5
C4		2

As we have observed from the base-case scenarios there is only one critical contaminant, namely C_2. Therefore scenarios 4 and 5 (Tables 4 and 6) include the regeneration of this contaminant. Analysis this particular two scenarios we have observed that, although the regenerated wastewater flow has closed value for both types of regeneration, there is a significant difference in what *total fresh water inflow* and *total wastewater outflow* concerns. In the presence of regeneration the fresh water consumption has decreased by 32% (Scenario 3 vs. Scenario 4), 28% respectively (Scenario 3 vs. Scenario 5). When the type of regeneration is FR (Scenario 5 – Table 4) the fresh water consumed has a 4% higher value than in the case when the model of regeneration is FO (Scenario 4). The difference in the fresh water consumption differs according to the regeneration type due to the fact that when there is a fixed value for the outlet contaminant concentration then the regeneration is performed until that limit is reached, independently on flow of wastewater. On the other hand, when the contaminant's regeneration has a fixed ratio it means that the actual outlet contaminant concentration may have a higher value than the value set in the other type of regeneration which obviously determines higher values of the subsequent streams.

Table 6

Overall mean availability

Scenario	C1	C2	C3	C4
1	848.73	2.96	1361.29	877.63
2	843.47	11.70	1361.15	887.90
3	825.69	10.03	1356.39	879.21
4	643.14	18.59	1304.14	859.67
5	661.52	14.53	1306.43	862.38
6	859.39	5.12	1355.49	878.79
7	857.32	5.20	1356.14	879.50
8	826.42	16.02	1352.23	879.44
9	826.42	16.02	1352.23	879.44
10	819.85	6.60	1353.5	879.35
11	826.42	16.02	1352.23	879.44
12	823.52	12.42	1358.18	879.30
13	826.71	4.48	1356.41	879.89
14	828.52	10.31	1361.47	880.50
15	831.06	10.57	1358.37	879.48
16	820.28	5.35	1354.34	879.35
17	826.42	16.02	1352.23	879.44

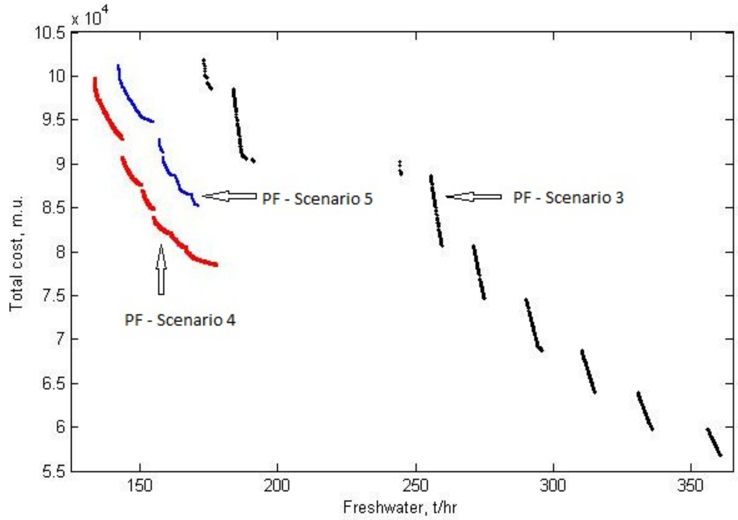


Fig. 3. Pareto fronts corresponding to Scenarios 3, 4 and 5 (see Table 4).

It is also important to notice that although the regeneration option is integrated within the WN, the values of MA (mean availability) in these two scenarios remain in the same region (Table 6). It would be meaningless to decontaminate the wastewater until a higher value of MA after regeneration is obtained because this will determine higher value for the fresh water flows and also for the internal flows which will be strongly reflected in the operating costs of the network.

For the remaining scenarios (6-17) we have drawn the same conclusion each time: regeneration cannot be used as a fine tuning tool for these networks' performances improvement. Some slight regeneration opportunities appear for contaminant C_1 (Scenarios 6 and 7) but does not determine a significant decrease neither in the fresh water consumption nor in the wastewater outflow.

Consequently, we have focused our attention on the thorough analysis of the most motivating scenarios (4 and 5) as these provide the incentives to use regeneration as a good option to minimize fresh water consumption at the same time with total costs decrease.

Fig. 3 presents the PF corresponding to Scenarios 3, 4 and 5 plotted on the same graph. We have observed that when the regeneration is not included the set of solutions distributes over a relatively large range (Scenario 3) in comparison with the cases with regeneration included. Basically the optimal solutions with regeneration included concentrate in a section of the PF where the PF corresponding to the Scenario 3 has few solutions. Comparing the trend lines of the PF corresponding to Scenario 4 and Scenario 5 we have observed that their variation is near-linear with higher costs in the case of Scenario 5 (fixed ratio regeneration).

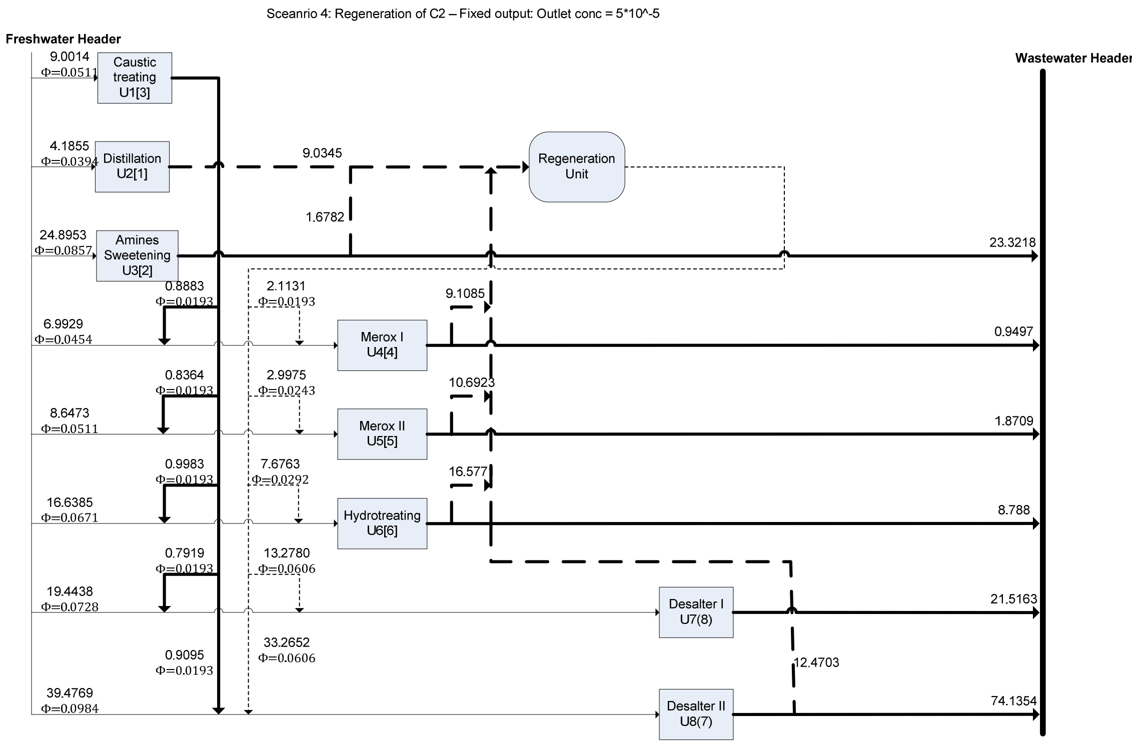


Fig. 4. Graphical representation of the WN corresponding to the point with the lowest value of the fresh water inflow from the Pareto front represented in Fig. 3.

From the previously described scenarios we have chosen for the graphical representation Scenarios 4 (Fig. 4) and Scenario 5 (Fig. 5).

The networks represented in Fig.s 4 and 5 reveal common features:

- the outlet wastewater flow of WU_1 and WU_2 is completely reused by the next ones in sequence, therefore these two units have no connection with the *wastewater header;*
- the outlet wastewater flow of WU_1 is completely reused without being regenerated;
- the units feeding the regeneration unit are WU_2 – completely and partially the next ones in sequence (except for WU_7 whose outlet wastewater flow is sent completely to treatment).

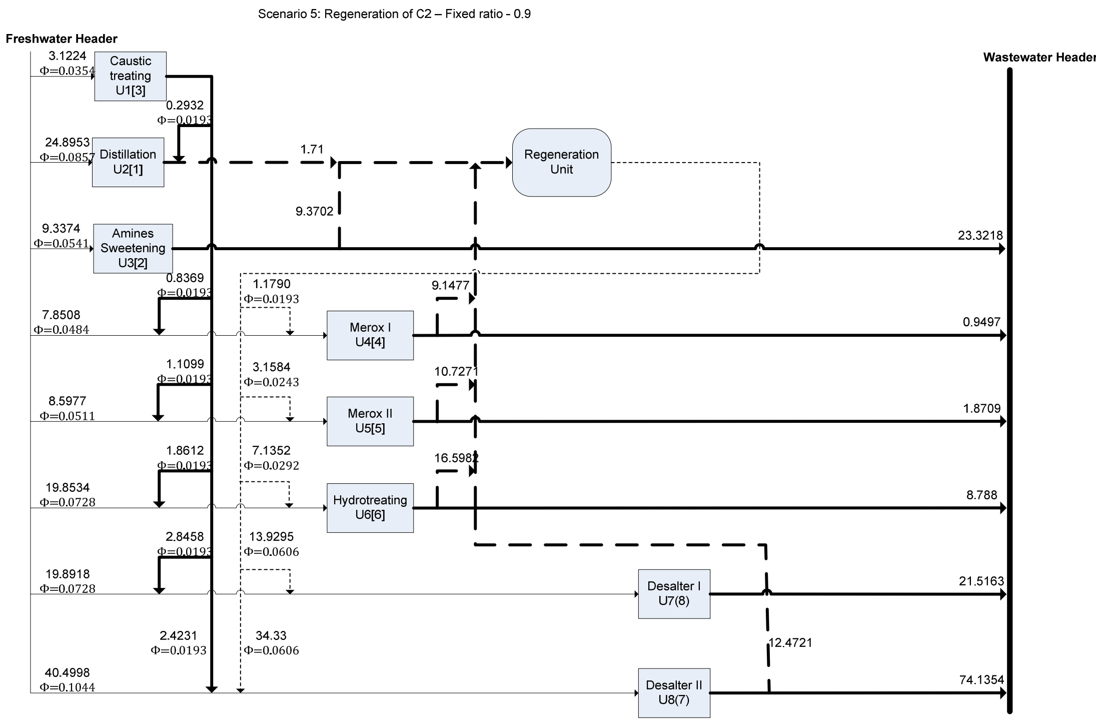


Fig. 5. Graphical representation of the WN corresponding to the point with the lowest value of the fresh water inflow from the Pareto front represented in Fig. 3.

5. Conclusions

The dual-objective optimization of a water/wastewater network has been presented in this paper with the goal of establishing whether the presence of a regeneration unit can be used a fine tuning tool to ensure minimization of fresh water consumption and operating and investment cost. The mathematical model describing the network has been developed, implemented in Matlab® (MathWorks®, MA) and the associated double-objective function has been minimized using Genetic Algorithms. The methodology has been applied on a real case study. Several relevant scenarios have been depicted (out of which three base-cases). Based on some previously defined criteria, for each scenario the contaminants to be regenerated have been determined. Two scenarios were meaningful from the study's point of view (Scenarios 4 and 5) as for them regeneration can be used as a considerably good option for fresh water minimization. The fresh water consumption dropped with 30% (average value) in the presence of regeneration.

A further potential development could focus on the optimization of the integrated water/wastewater networks with local regeneration options.

Acknowledgments

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Acronyms:

WN – water network; WU – water-using unit; RU – regeneration unit
GA – genetic algorithm; FWC – fresh water consumption;TC – total cost; FO – fixed output;
FR – fixed ratio; TOPSIS - Technique for Order Preference by Similarity to Ideal Solution
GEC - Global Equivalent Cost (T h^{-1}); MA – mean availability; PF – Pareto front

R E F E R E N C ES

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