RETROFIT OF WATER NETWORKS IN PROCESS PLANTS

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Abstract. In this paper, we present a methodology for the retrofit of water utilization systems using mathematical optimization. The problem consists of determining the best re-piping and the capacity of a new treatment unit (if any) to be introduced to generate the best retrofit. Instead of reducing water consumption, or maximizing savings, we resort to analyze the problem using a more comprehensive view of savings and return of investment (ROI) within feasible freshwater usage ranges. The example shows that the solutions where savings and ROI are maxima are remarkably different.

Keywords: Retrofit, maximum savings, profitability.

1. Introduction

Retrofit projects are widely required in the industrial sector for many reasons, like capacity increase needs, improvement in product quality, law requirements for product or byproducts, environmental regulations, among others. One of the important issues concerning retrofit projects of water/wastewater systems are new environmental targets. There are, however, economics incentives that come from cost reductions. While performing a retrofit to meet environmental targets could be mandated, retrofits to reduce freshwater costs as well as water treatment costs are not.

As highlighted by Nourai et al. (2001), a cost effective retrofit project looking at reducing the environmental impact should have a precise description of the plant, be realizable in practice and the pollution impact should be fully defined in practical terms.

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Even if the physical features are very well defined, precise cost estimation is still primordial to reach the best retrofit alternative. This important implication is detailed discussed by Taal et al. (2003).

Bagajewicz et al. (2000) proposed a method to solve grassroots and retrofit problems minimizing total cost (including cost with freshwater, capital cost and pumping cost). Setting aside the need to approach the retrofit problem trying to meet environmental targets or maximize savings, the management point of view (maximum return of investment) is still important in any competitive environment. Some standard measurements of profitability commonly applied are return on investment (ROI), payback period (PBP), net present worth (NPW) and internal rate of return (IRR). Addressing this important issue, a management view using Pinch principles was presented by Zhelev (2005) as applied to industrial energy projects. The methodology uses a grid diagram analogous to Water Pinch, but targets optimum profitability. The case study used is for an energy recovery project. It analyzes three options with the same energy saving seeking maximum profit.

Another issue in the solution of these problems is the imprecision of data. To deal with imprecise process data, Tan and Cruz (2004) applied a symmetric fuzzy linear programming to single contaminant retrofit problems using either a model based on mass exchange units and source/sink allocation.

In this paper an attempt to approach a wider view of retrofit options using economic, consumption and profitable point of view is proposed. To deal with uncertainty of data, a sensitive analysis of the mass loads is performed on the solutions. There are, however, better methods to address this issue, which will be used in future work.

This paper is organized as follows: We first present the Problem Statement, then we show the Retrofit Models followed by the Solution Methodology. Finally, a simple example is discussed.

2. Problem Statement

Given an existing industrial water network (water-using units, freshwater source, and end-of-pipe treatment) which must be retrofitted, it is desired to determine what re-piping and what capacity of a new treatment process (if any) is needed to maximize targets (profit, savings or flexibility). The technical parameters given by the current network are the flowrates, maximum inlet and outlet concentrations and mass load of the water-using units and freshwater concentration. The new regeneration process has a fixed outlet concentration and no flowrate limitations were imposed. The economic parameters include the cost of freshwater, operational costs of the end-of-pipe treatment and the regeneration process and the capital cost of the new connections and the new regeneration process.

3. Retrofit Model

The constraints for the retrofit model are the following:

Balance of water in the units:

$$FW_{m*} + FNU_{m*} + \sum_{m \neq m*} FUU_{m,m*} = FUN_{m*} + FS_{m*} + \sum_{m \neq m*} FUU_{m*,m} \quad \forall m* \tag{1}$$

Balance of water in the new treatment process:

$$\sum_{m} FUN_{m} = FNS + \sum_{m} FNU_{m*} \tag{2}$$

Balance of the contaminant in the units:

$$FW_{m*} * C^{ws} + FNU_{m*} * C^{n} + \sum_{m \neq m*} FUU_{m,m*} * C_{m}^{out} + \Delta m_{m*} = \left(FUN_{m*} + FS_{m*} + \sum_{m \neq m*} FUU_{m*,m} \right) * C_{m*}^{out} \quad \forall m* \tag{3}$$

Limit of inlet concentration on the units:

$$FW_{m*} * C^{ws} + FNU_{m*} * C^{n} + \sum_{m \neq m*} FUU_{m,m*} * C_{m}^{out} \leq \left(FW_{m*} + FNU_{n,m*} + \sum_{m \neq m*} FUU_{m,m*} \right) * C_{m*}^{\max,in} \quad \forall m* \tag{4}$$

Limit of outlet concentration on the units:

$$C_{m*}^{out} \leq C_{m*}^{\max,out} \quad \forall m* \tag{5}$$

Existence of new connections: These constraints are used to apply the capital cost of the new connections. Binary variables (*Y)* are used to determine if a new connection is established. These are the classical big M constraints.

$$FUN_m \le U * YUN_m \qquad \forall m \tag{6}$$

$$FNU_m \le U * YNU_m \qquad \forall m \tag{7}$$

$$FUU_{m*,m} \le U * YUU_{m*,m} \qquad \forall m*, m \tag{8}$$

$$FNS \le U * YNS \tag{9}$$

Regeneration Capacity

The flowrate through the regeneration unit is limited by the unit capacity, which is expressed in flowrates terms and in this work, not related to removing load

$$\sum_m FUN_m \le RegCap \tag{10}$$

The regeneration capacity (*RegCap*) is in some instances treated as a variable (design mode) or as a parameter (evaluation mode), as decribed below.

3.1. Objective Function

Let F^{old} be the existing system freshwater consumption, which is a fixed value and assume that operational costs are direct function of flowrates (freshwater and regenerated flowrate); then, the following objective function maximizes savings:

$$Max\left(\left(\left(F^{old} - \sum_m FW_m\right) * (\alpha + eop) - OPN * \sum_m FUN_m\right) * OP - FCI * af\right) \tag{11}$$

The first part of the equation represents the savings obtained from freshwater and end of pipe treatment flowrate reduction. In this expression, FW_m and α are the flowrate and cost of freshwater, respectively, and *eop* the cost of the end-of-pipe treatment. In the second part , *OPN* is the operational cost of the newly added regeneration process and FUN_m are the flowrates between the water using units and the regeneration process. Treatment requires chemicals and therefore there is an associated cost. However, if one assumes that the efficiency of the usage of these chemicals, that is, the amount of chemicals per unit pollutant removed is the same for both the end of pipe treatment and the new regeneration unit, this cost is fixed for any network because the load removed in all process units, and consequently the combined load treated in both treatment units is also fixed. Therefore, one can ignore it. Finally, the last term is the annualized capital cost invested in the retrofit, where *FCI* is the fixed capital cost and *af* is the discount factor. This factor is based on the number of years that the investment will be paid and the discount rate. The fixed capital of investment is calculated as follow:

$$FCI = \sum_m \left(YUN_m * ICUN_m + YNU_m * ICNU_m + \sum_{m^* \neq m} YUU_{m,m^*} * ICUU_{m,m^*} \right) + YNS * ICNS + ICN * \left(RegCap\right)^{0.7} \qquad (12)$$

In Eq. (12), the first part, inside the parenthesis, represents the capital costs with connections between the regeneration process and water using units and among water using units. The second part corresponds to the capital costs of the connection between the new regeneration processes and the end of pipe treatment. The last term of the equation is the capital cost of the new regeneration treatment. It is considered to be a function only of the regeneration process capacity, which is expressed in terms of flowrate, and not load to remove. The *ICs* are the investment needed for the new connections. Finally, the return of investment is given by:

$$ROI = \frac{\left(\left(F^{old} - \sum_m FW_m\right) * \left(\alpha + eop\right) - \sum_m \left(OPN * FUN_m\right)\right) * OP}{FCI} \qquad (13)$$

3.2. Solution Methodology

The methodology applied in this work intends to analyze the behavior of maximum savings and ROI for a range of feasible freshwater flowrate in new networks. To solve the problem, the freshwater flowrate is fixed and the problem is solved. The freshwater flowrate is first varied through the “range of reuse”, which is defined as being between the minimum freshwater consumption (obtained minimizing it with the current model) and the current one. Subsequently, when savings are maximized for the aforementioned fixed freshwater flowrates inside this range, the respective FCI’s are calculated and the corresponding ROI is obtained. Plotting these results (Savings, FCI or ROI vs. Freshwater flowrate), different points correspond to different networks and also different capacities of the regeneration unit (when it shows up) are obtained.

Therefore to obtain the final solution, the following steps are carried out:

1. Each network (new connections established by *Y*) is fixed and the resulting NLP model is used to determine the minimum freshwater flowrate for which this network is feasible. A new range will then be given by this new minimum freshwater flowrate and the freshwater flowrate of the current network. We call this the feasible freshwater consumption for each network. Then, the NLP is solved for each network maximizing savings.
2. The new profiles are investigated and capacity sizes of the regeneration process are chosen. For each suggested connections configuration, and for one fixed regeneration unit capacity, the NLP model is used to maximize the savings throughout its feasible freshwater consumption range.
3. Then, limits of the regeneration process capacity for each network are determined. These limits are based on where each network is economically superior (maximum savings among all network options).
4. Finally, the best option is chosen based on the chosen target (Savings or ROI)

4. Example

The following example was adapted from Example 1 of Wang and Smith (1994). The limiting process data for this problem are shown in Table 1 and it has a minimum freshwater flowrate without reuse of 112.5 ton/hr.

Table 1. Limiting process water data.

Process Number	Mass load of contaminant	C_{in} (ppm)	C_{out} (ppm)	Water flowrate	Minimum Freshwater usage
1	2 kg/h	0	100	20 ton/h	20.0 ton/h
2	5 kg/h	50	100	100 ton/h	50.0 ton/h
3	30 kg/h	50	800	40 ton/h	37.5 ton/h
4	4 kg/h	400	800	10 ton/h	5.0 ton/h

The cost of freshwater was considered $0.3/ton, the annual operation 8600 hr/year. The freshwater concentration was assumed to be equal to zero and the end of pipe (handled as a sink) is not limited either by concentration or flowrate. However it has an operational cost of $1.0067/ton. Finally, ICN is $16,800 and the operational cost of the regeneration process is assumed to be $1.00/ton.

As the current network has only the connection between the water source and units and between units and the sink, the investment costs of new connections are needed and they are presented in Table 2. A factor for capital cost (*af*) of 0.1 per year was assumed.

The feasible “range of reuse” found for the studied water network is between 20 ton/hr (the minimum flowrate using a regeneration process) and 112.5 ton/hr (flowrate of the current network).

Table 2. Capital costs of the connections.

	Unit 1	Unit 2	Unit 3	Unit 4	Reg.	End of pipe treatment
Unit 1	-	$150,000	$110,000	$45,000	$145,000	-
Unit 2	$50,000	-	$134,000	$40,000	$37,000	-
Unit 3	$180,000	$35,000	-	$42,000	$91,000	-
Unit 4	$163,000	$130,000	$90,000	-	$132,000	-
Reg.	$33,000	$130,000	$50,000	$98,000	-	$45,000

Figure 1 shows the savings as a function of flowrate. The discontinuities occur when a different network is obtained. As explained above, for networks A through D, a different capacity of the regeneration unit is associated to each point of these curves. We note that, although it looks like these are straight lines, some are not, as it will become obvious later. The ranges of freshwater where each network is the economical optimal solution (maximum savings), obtained using discretization of the freshwater range are shown in Table 3. These configurations (A to G) are presented in Figs 2 to 8. The flowrates and concentrations shown correspond to the point of maximum savings.

The final concentration of the stream going to the end of pipe treatment of the suggested networks differs. In the case where no regeneration process is necessary, the variations are between 456ppm (when the freshwater consumption is 90 ton/h) and 365ppm (the current network – 112.5 ton/h). For example, looking networks A and B, the concentration of the stream going to the end of pipe treatment increases from 400ppm to 800ppm. On the other hand, the inlet concentration of the regeneration process is 460 ppm in the first case and 172 ppm in the latest. As it was pointed out in earlier, these differences have no effect on the cost of regeneration and final treatment. This is because it was argued that the load of contaminants to remove is constant for both and therefore the cost of the corresponding chemicals is also constant, leaving only the cost of moving fluids to be accounted for. If the cost of cleaning becomes a nonlinear function of concentration or even if linear if it has a different cost coefficient in the regeneration unit than in final treatment, then these differences in concentration matter. We leave this matter for future work, as this is not the main point of this article.

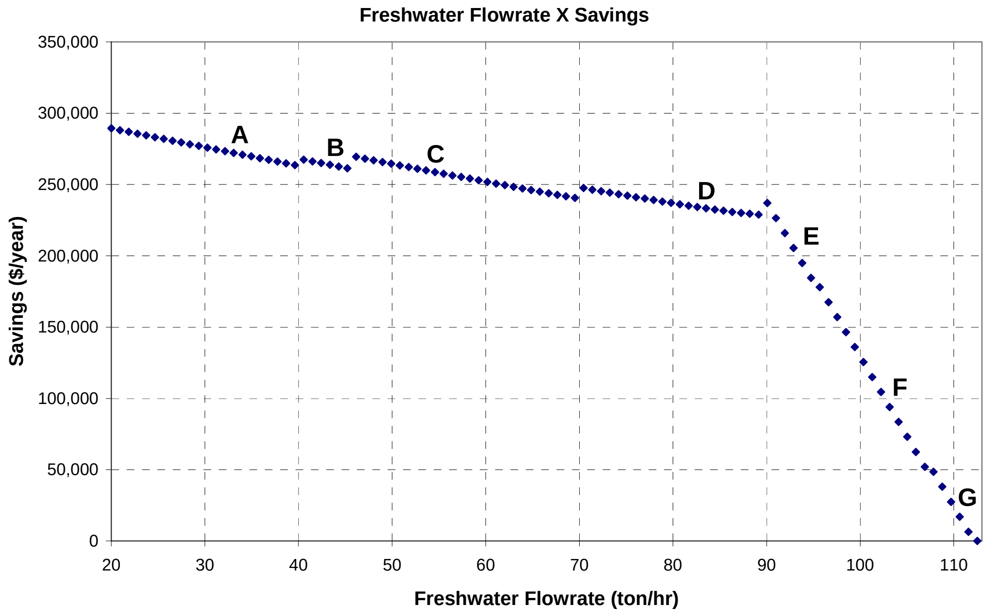

Fig. 1. Savings as a function of Freshwater flowrate.

Table 3 – Network and corresponding range of freshwater flowrate (Figure 1).

Network	Range of freshwater usage (discrete values)	New Connections	FCI of New Connections
A	20.00 to 39.621 ton/hr	U1-U3, U2-U4, R-U2, R-U3, U2-R, U3-R	$458,000.00
B	40.556 to 45.227 ton/hr	U1-U3, U2-U4, R-U2, U2-R, U3-R	$408,000.00
C	46.162 to 69.520 ton/hr	U1-U3, U2-U4, R-U2, U2-R	$317,000.00
D	70.455 to 89.141 ton/hr	U1-U3, U2-U4, R-U3, U2-R	$237,000.00
E	90.076 to 94.747 ton/hr	U1-U3, U2-U4	$150,000.00
F	95.682 to 106.894 ton/hr	U1-U3	$110,000.00
G	107.828 to 111.566 ton/hr	U2-U4	$40,000.00

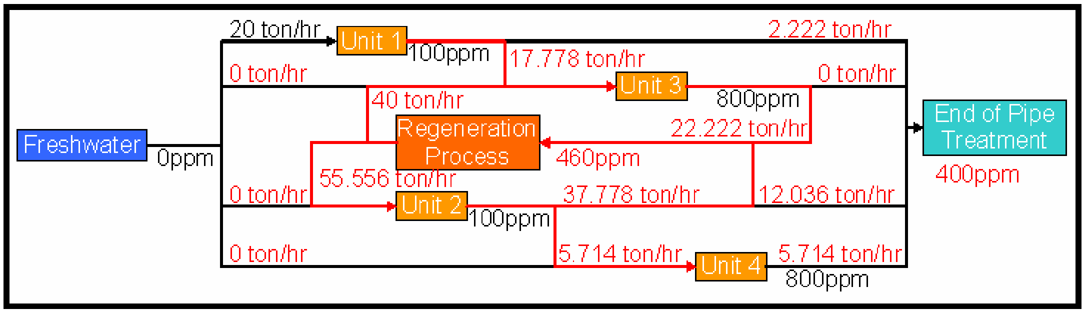

Fig. 2. New connections configuration A.

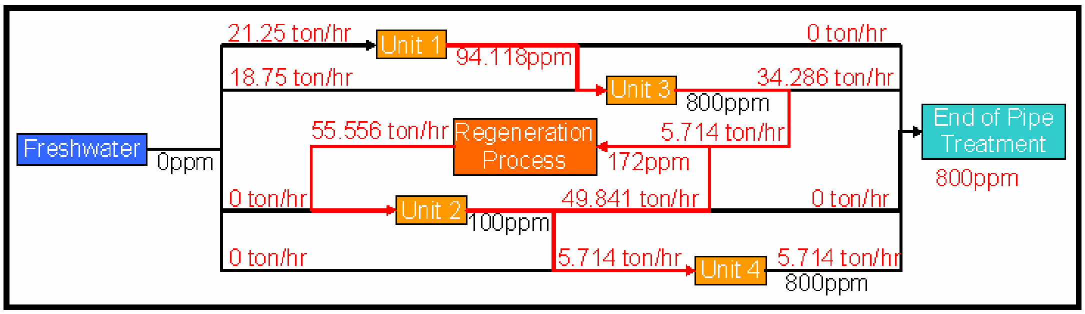

Fig. 3. New connections configuration B.

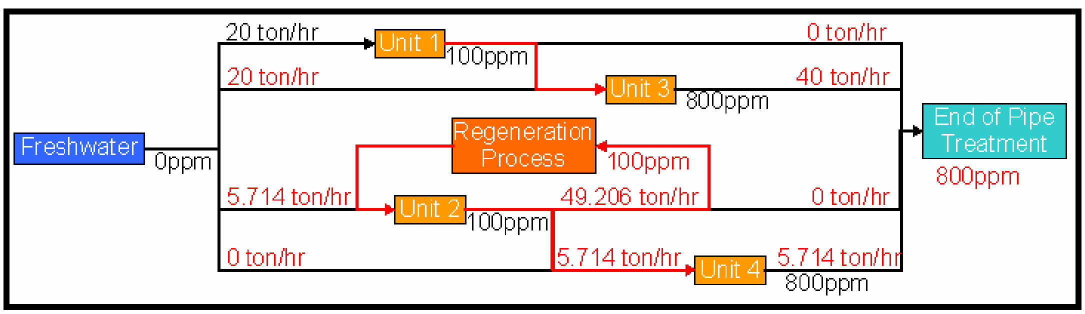

Fig. 4. New connections configuration C.

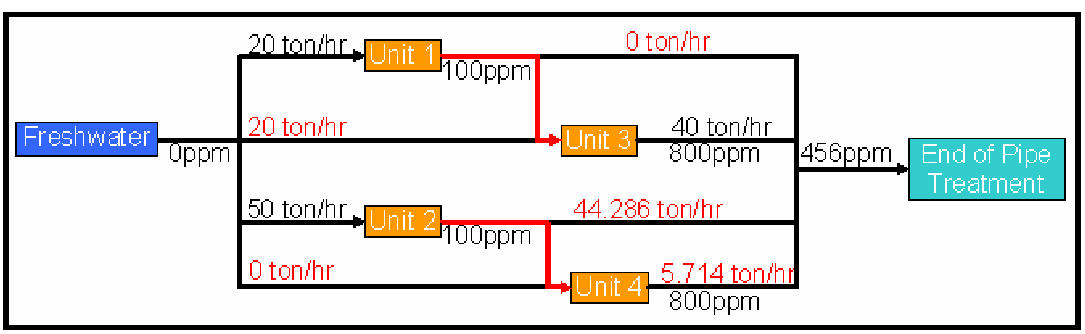

Fig. 5. New connections configuration D.

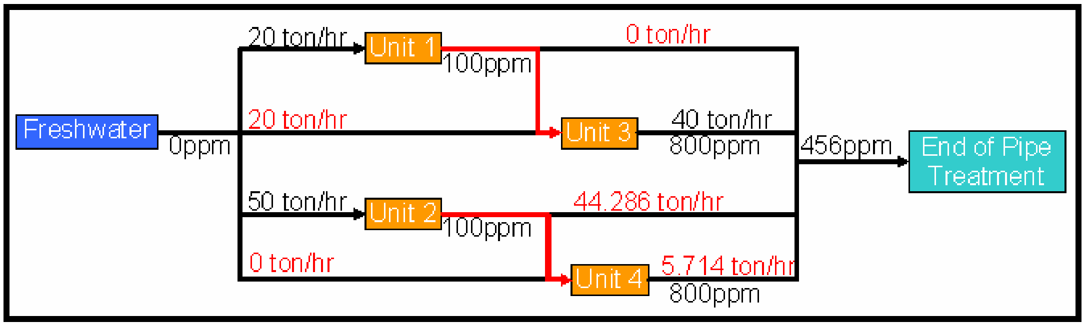

Fig. 6. New connections configuration E.

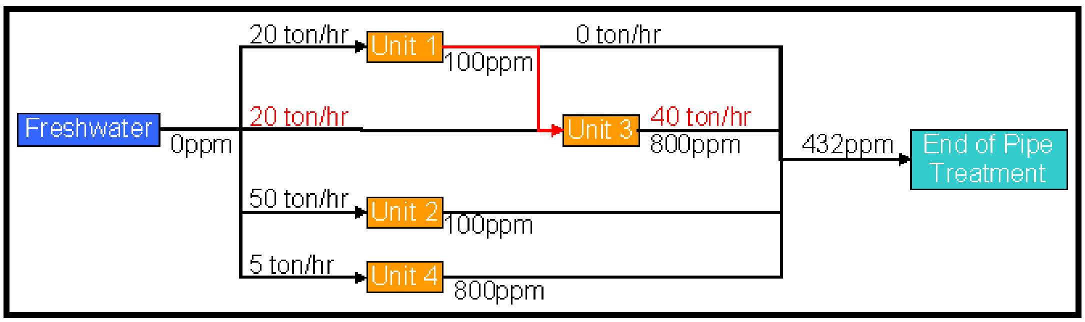

Fig. 7. New connections configuration F

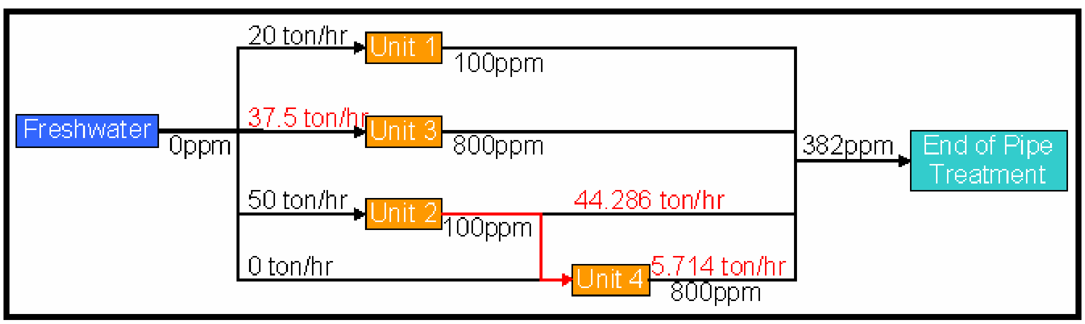

Fig. 8. New connections configuration G.

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The FCI and then the ROI for the feasible range of freshwater flowrate are analyzed next. The FCI and ROI profiles are shown in Figures 9 and 10, respectively. Savings and FCI go down (in a discontinuous manner). However, the ROI increases. Therefore, one can conclude that maximizing savings does not necessarily generate the most profitable solution. ***Indeed, the most profitable option (highest ROI) happens at the limit of 95 ton/hr (Network F), where no regeneration process is needed. Conversely, Network A exhibits the highest savings.***

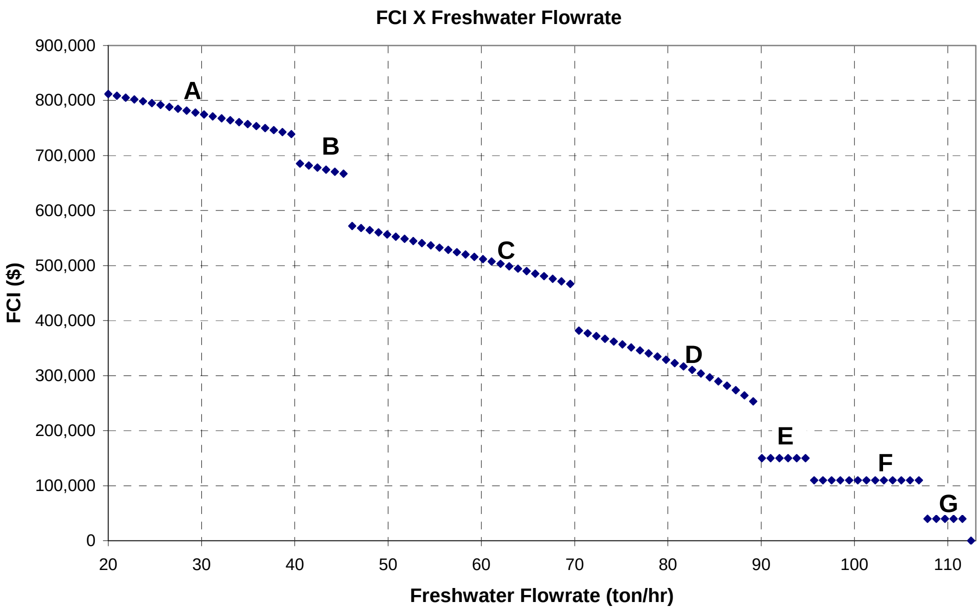

Fig. 9. FCI as a function of Freshwater Flowrate.

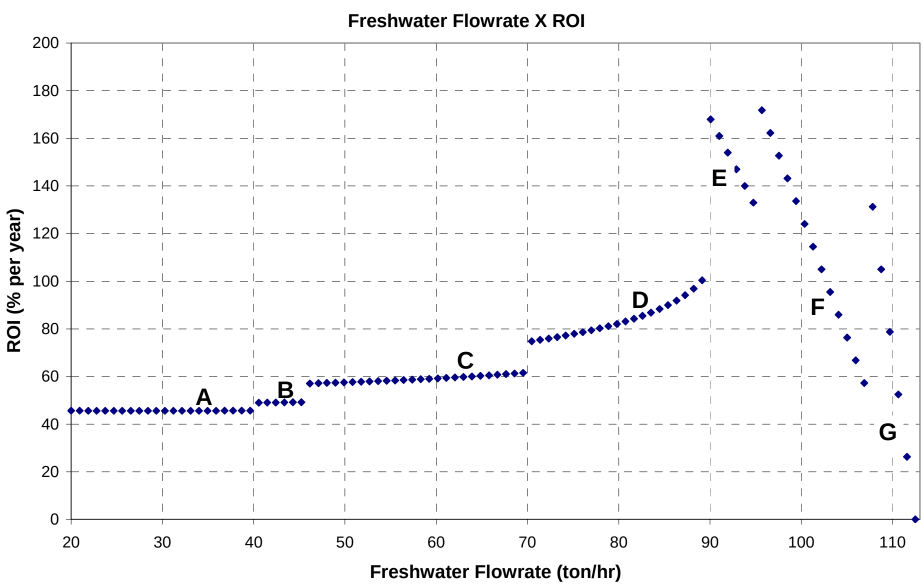

Fig. 10. ROI as a function of freshwater flowrate.

Although the connections are the same for each continuous curve in Figures 8 to 10, each point corresponds to a regeneration unit that has a different size for different total freshwater usage changes. Interestingly, the regeneration unit size and the freshwater usage for Figures 1, 9 and 10 are proportional. This does not seem to have a direct simple explanation. To extend the feasibility range of each network, we now solve the problem again (fixing the network, but not the size of the regeneration unit yet) for minimum freshwater usage to establish the feasible freshwater consumption of each network (between the minimum found and the current usage).

The overlapping solutions for all networks with regeneration are shown in Figure 11. The aforementioned linear relation between the regeneration capacity and the freshwater flowrate remains valid for each networks from its maximum saving to the minimum flowrate without regeneration (when the regeneration capacity is zero). This regeneration capacity scale is also shown in the scale above the figure. Thus, the interesting point to make here is that at certain freshwater flowrate, the network with maximum saving obeys this linear relationship and, all the other feasible networks at this freshwater consumption have the same regeneration capacity as well. Another thing worth point out is that, to construct the curves, the minimum freshwater flowrate obtained for a fixed network may not coincide with the original minimum value of the freshwater usage range at maximum savings. When this happens, one may get isolated points, like the one shown in Figure 11 for network C. This isolated point of network C represents a feasible condition of this network where it operates economically worse then the previous network B. Since this point does not represent the maximum savings at this freshwater consumption, the regeneration flowrate scale is no longer valid for it. The corresponding ROI profiles are shown in Figure 12.

In the next step, we fix the size of the regeneration network in addition to the connections. We pick the sizes that correspond to the capacity obtained for the point with maximum savings of each network In addition, an additional lower size was used in network C (the maximum for network D). The savings are now linear for the whole feasible freshwater consumption range, as shown in Figure 13. In this figure, the previous curves of the networks with regeneration are included for reference. The capacities of the regeneration units correspond to where the straight line touches or departs from the corresponding curved profile of savings. Once the regeneration capacity is defined, the minimum freshwater consumption is determined by the freshwater flowrate scale (in the bottom).

This evaluation is useful to define economical limit sizes of the regeneration process for the different networks. For each network, a regeneration process with capacity higher than the maximum values used to construct Figure 13 does not decrease the freshwater consumption without generating a saving that is lower than one of another network. Consequently, in the best case (when freshwater consumption does not decrease), the operational part of the savings equation does not change while FCI increases. Even thought, a higher regeneration capacity generates economic loss.

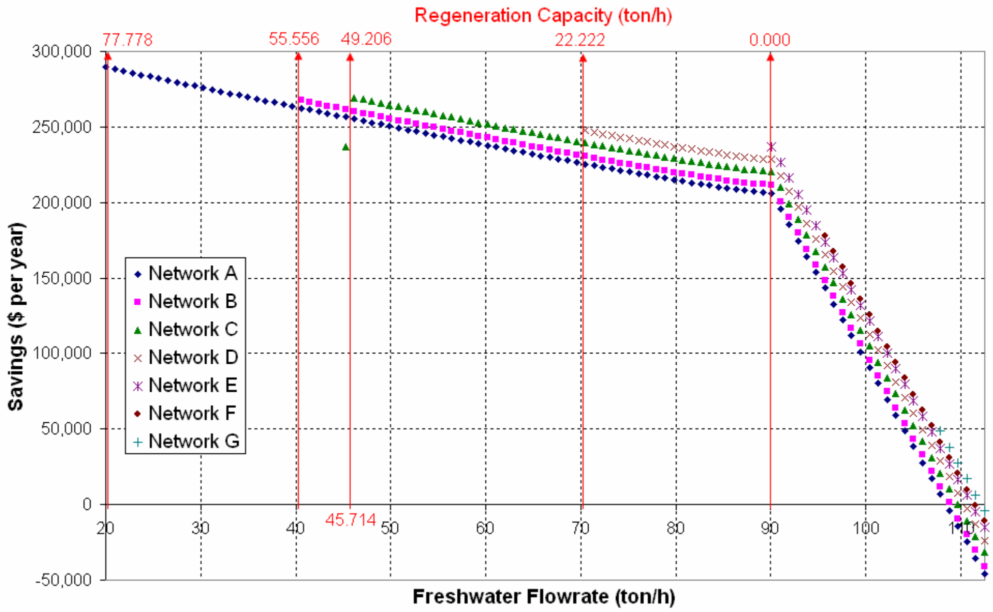

Fig. 11. Savings profile of the suggested networks.

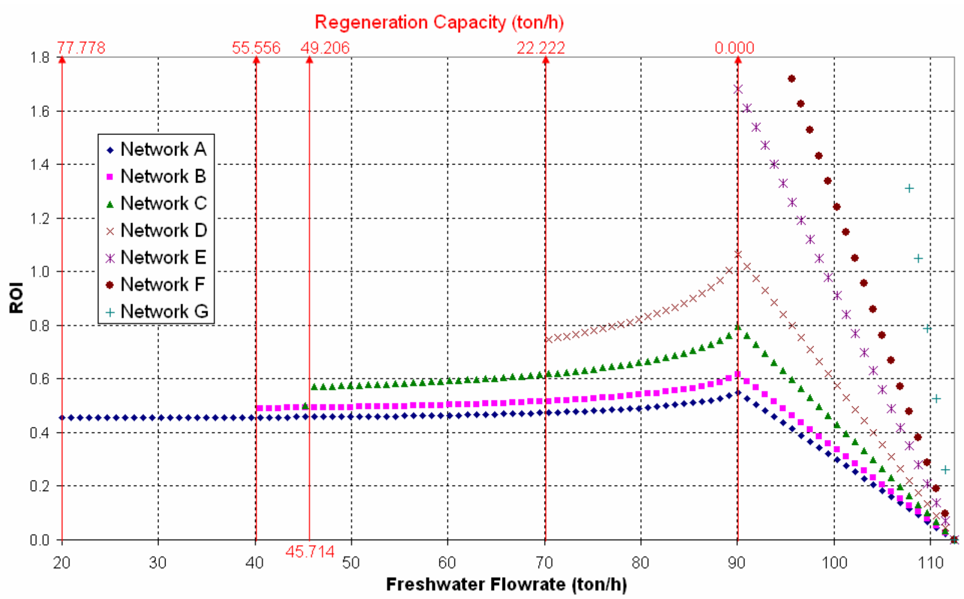

Fig. 12. ROI profile of the suggested networks

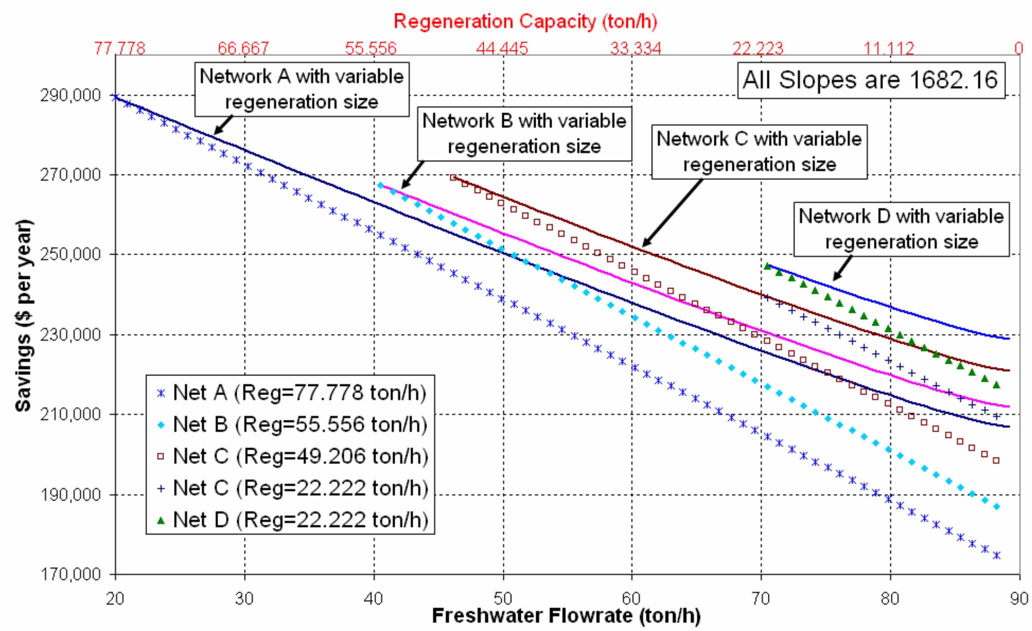

Fig. 13. Savings profile for fixed sizes of the regeneration process.

One can see (Figure 13) that a regeneration process with 22.222 ton/h capacity will be economically superior when used in network D that when used in network C. This also happen with Network A and B with 22.222 ton/h capacity. If we draw the profile, they will be below of the one in network D. Similarly, a regeneration system with 49.206 ton/h capacity is economically superior when used in network C that in network B and one with 55.556 ton/h capacity is economically superior in network B than in network A. Further, from the economical point of view, network A should not work with a regeneration process with capacity lower then 61.345 ton/h and, as suggested before it should not work with a regeneration process with capacity higher than 77.778 ton/h. This lower limit capacity represents the regeneration capacity in network A that generates the same savings than maximum posterior savings generates by other network (in this case, network C). This point represents also the upper limit economically optimum of network C (49.206 ton/h). Besides, as one can see, network B does not present any economical advantages. The only reason that it can be considered is for consumption issues when compared with network C. Similarly, the limits for network C are between 49.206 ton/h and 29.695 ton/h (this lower limit generates the same savings that network D at its maximum savings). In turn, network D has the limit between

22.222 ton/h and 12.104 ton/h (this lower limit generates the same savings that the maximum savings in network E – the highest savings between the options without regeneration). Finally, the use of a regeneration process with capacity outside these intervals generates economical losses. This process of thought is illustrated in Fig. 14.

The ROI profiles of the networks A to D with fixed size of regeneration process and also of network D are presented in Figure 15. The largest advisable sizes are used in these profiles. The pattern of straight lines repeats, but they are not parallel anymore.

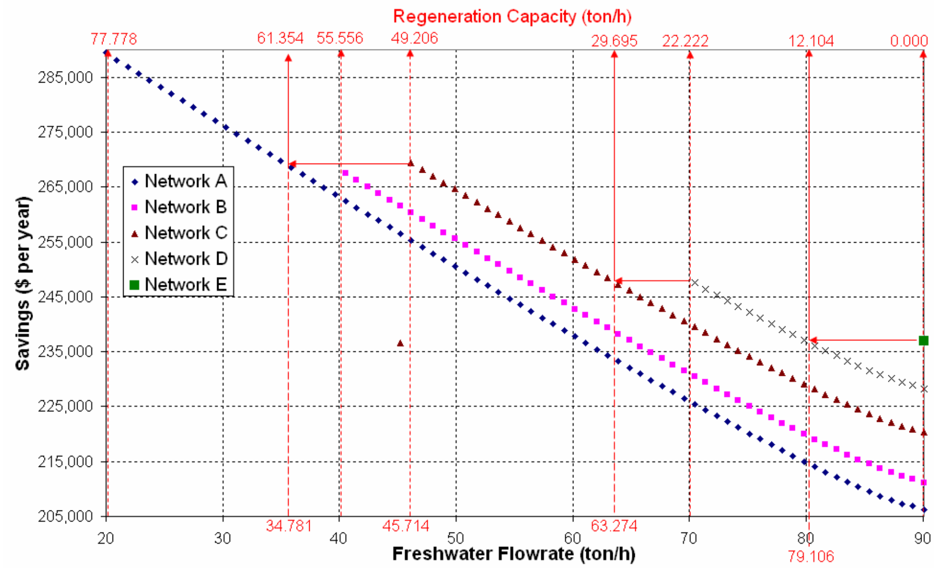

Fig. 14. Analysis of regeneration capacity.

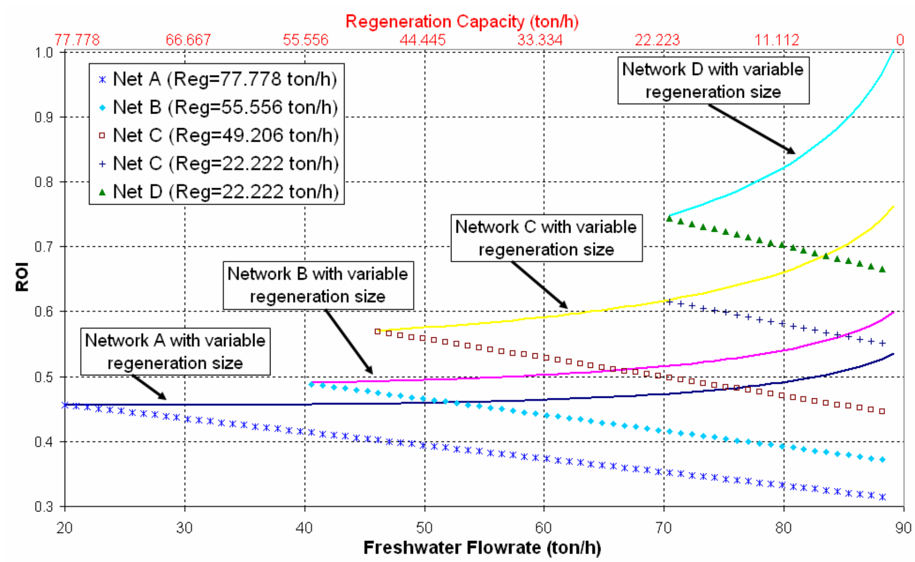

Fig. 15. ROI profile for the limit sizes of regeneration process.

4.1. Sensitivity Analysis

We now present a sensitivity analysis of the mass load as a starting point to analyze the effect of uncertainties. It is applied to the network D and F which are the most profitable options with and without regeneration process respectively. Network D uses a 22.22 ton/h regeneration capacity. In each case, the mass load of the specific unit was varied +/-25% while the mass load of the others was kept in their nominal level. While the network was fixed and the capacity of the regeneration system was set at the aforementioned maximum limit, the problem was solved to obtain the value of the maximum saving and the respective value of freshwater usage at each new mass load condition. Figures 16 to 19 show the results, while the extreme cases, where all mass loads are in their lower and higher value, are presented in Table 4.

From the sensitivity analysis applied varying individual units is possible to see that mass load variation of Unit 4 has no influence in the savings of the network D and a small influence in network F. The influence in network F appears due to this unit to be feed only by freshwater, differently form network D. Also, Unit 2 appears as being the one that presents the larger influence. In network D the maximum savings are achieved by changes in both freshwater usage and regenerated flowrate. On the other hand, network F does not have a regeneration process, and then the only way to accommodate mass load variation is to increase the freshwater consumption. However, for Unit 2, network D accommodates the variation of mass load also changing the freshwater rate. When the extremes are analyzed (Table 4), the configurations remain feasible because there is always the possibility of to go back to the old connections. However, as in the previous results, changes in freshwater flowrate and/or regenerated flowrate are needed. Consequently, the maximum savings achieved change.

The results for the extreme cases point that at the high extreme both networks will have a negative saving. However, the profit is positive in network D and negative in network F. Moreover, at the high extreme, network F would have a higher consumption than the original network at nominal mass loads and the expenses would be higher then the payment for the capital invested. Finally, network D has larger savings than network F in all cases. In addition, except for the high extreme case, network D has higher ROI.

Thus, if freshwater is largely available, network F should be strongly considered since it represents the most profitable option. However, if freshwater is, or might become limited, network D should be preferred. Once the freshwater is limited to be smaller than 118.75 ton/h, network F is infeasible at high extreme mass load variations.

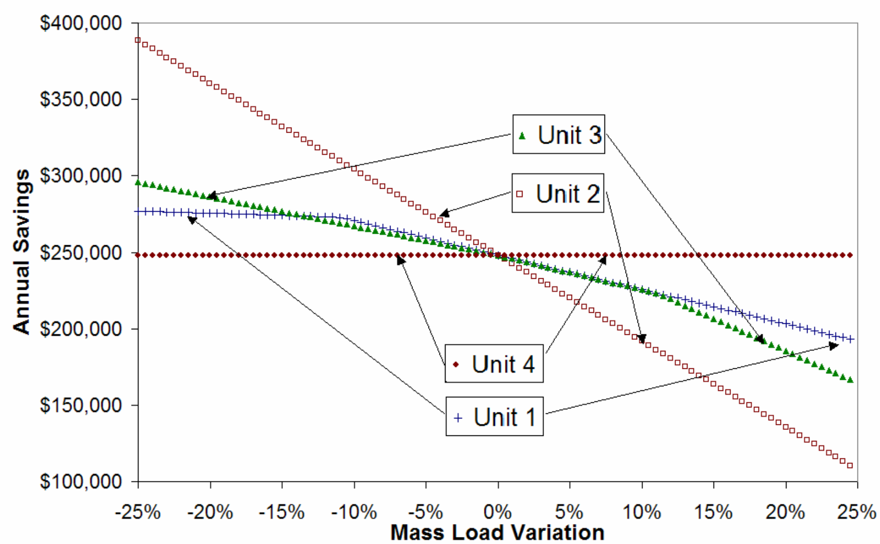

Fig. 16. Sensitivity analysis of network D with 22.222 ton/h regeneration capacity

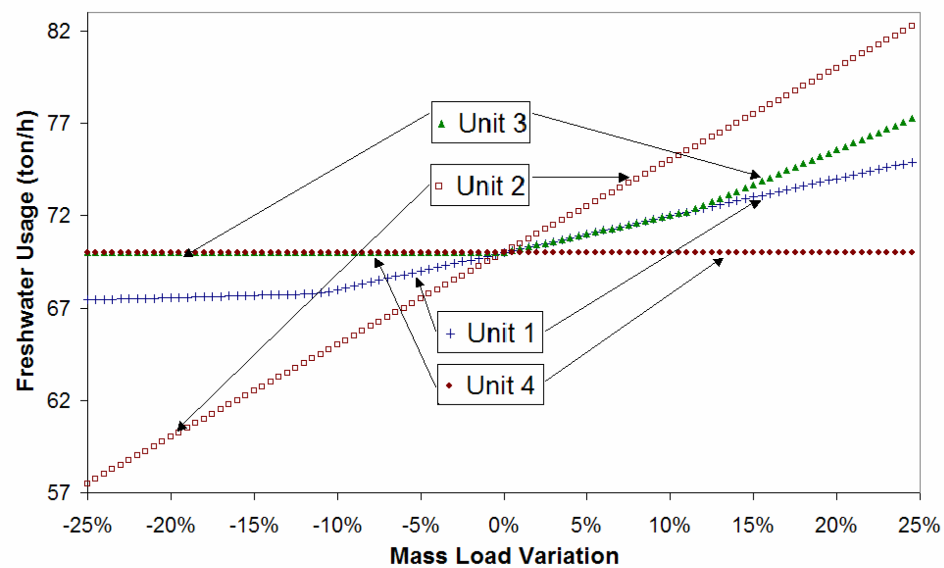

Fig. 17. Sensitivity analysis of network D with 22.222 ton/h regeneration capacity

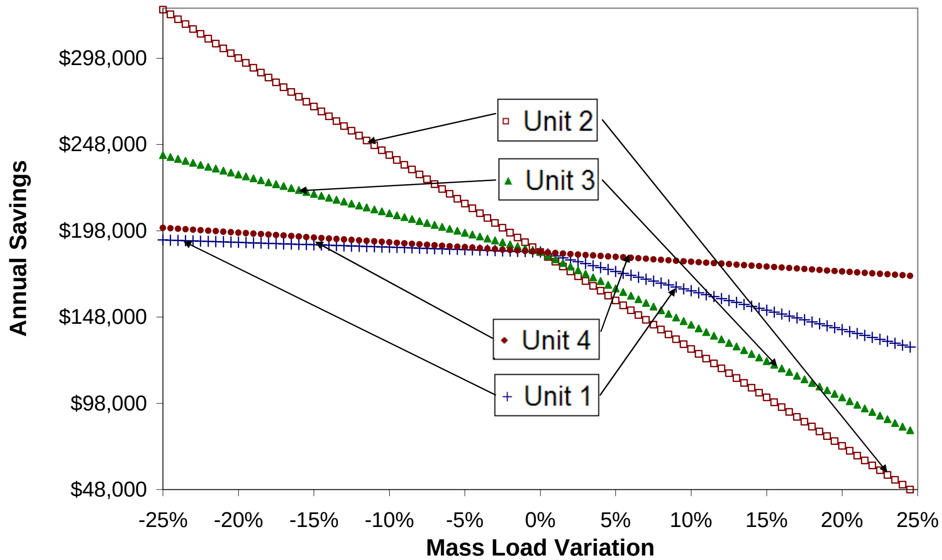

Fig. 18. Sensitivity analysis of network F

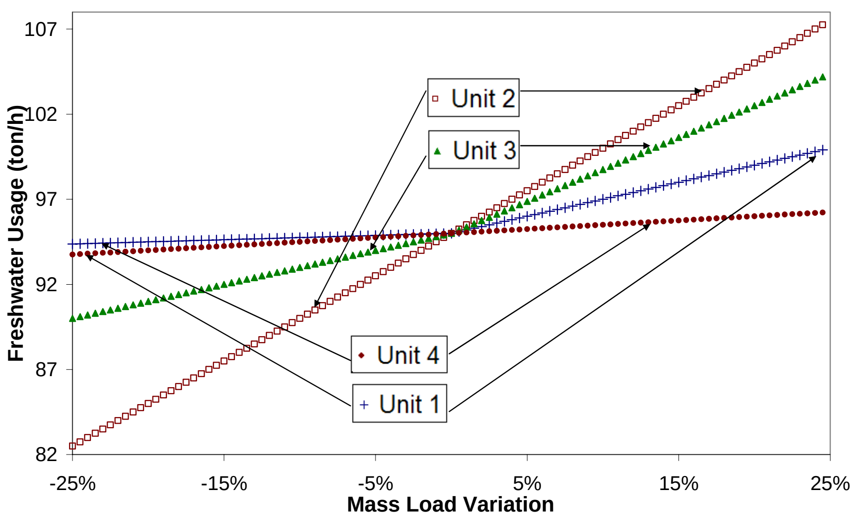

Fig. 19. Sensitivity analysis of network F

Table 4. Sensitivity analysis of the extreme cases

Mass Load Variation	Low		High	
	Network D	Network F	Network D	Network F
Saving ($ per year)	492,498.79	452,551.82	-4,784.12	-81,235.12
ROI (% per year)	138%	421%	9%	-64%
Freshwater (ton/h)	52.5	71.25	92.5	118.75

5. Conclusions

This paper introduced a methodology to perform the retrofit of water/wastewater systems considering regeneration based on mathematical optimization and profitability insights. Besides, it allows to analyze different option to allocation of new connection, the methodology is also useful to decide the optimum interval of regeneration process capacity for each network The results also point at an important conclusion: Targeting maximum savings does not necessarily generate the most profitable solution.

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Nomenclature

Parameters

$C_m^{\max,in}$ – Maximum inlet of water-using unit *"m"*

$C_m^{\max,out}$ – Maximum outlet concentration of water-using unit *"m"*

C^{ws} –Concentration of the water source

C^{n} –Concentration of the treatment process

Δm – mass load

α – cost of freshwater

eop – cost of the end of pipe treatment

af – Annual factor.

OP – hours of operation per year.

OPN – Operational cost of the new regeneration processes

$ICUN_m$ – Investment costs of connection between a water-using unit *"m"* and the new regeneration process

$ICNU_m$ – Investment costs of connection between the new regeneration process and a water-using unit *"m"*

$ICUU_{m,m*}$ – Investment costs of connection between the water-using unit *"m"* and water-using unit *"m*"*

ICNS – Investment costs of connection between the new treatment process and the sink

ICS – Pre-factor of the investment costs of the new regeneration process

ROI – Return on investment

FCI – Fixed capital cost

Variables

FW_m – Flowrate between the source of freshwater and water-using unit *"m"*

FUU_{m,m^*} –Flowrate between water-using unit *"m"* and water-using unit *"m*"*

FNU_m –Flowrate between the new regeneration process and water-using unit *"m"*

FUN_m –Flowrate between water-using unit *"m"* and the new regeneration process

FNS –Flowrate between the new regeneration process and the sink

FS_m –Flowrate between water-using unit *"m"* and the sink

C_m^{out} – Outlet concentration of unit *"m"*

RegCap – Regeneration capacity (it is a parameter in the last part of the methodology)

Binaries (variables for MINLP model and parameters for NLP model)

YUU_{m,m^*} – New connections between water-using unit *"m"* and water-using unit *"m*"*

YNU_m – New connections between the new regeneration process and water-using unit *"m"*

YUN_m – New connections between the water-using unit *"m"* and the new regeneration process

YNS – New connections between the new regeneration process and the sink

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