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Scheduling of the membrane module rotation in RO desalination plants

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ABSTRACT

This work deals with the optimization, in reverse osmosis desalination plants, of the scheduling of membrane cleanings and rotation of the membrane modules inside each pressure vessel. Each pressure vessel consists of several membrane modules (typically around seven) in series. The modules closer to the feed inlet are prone to be damaged by biofouling and solids, while the modules closer to the reject outlet are prone to be damaged by scaling due to increased salt concentration. Besides, the permeate flux varies for different modules along the pressure vessel. In order to increase the life of the membrane modules, it is a good practice to rotate the modules, thus spreading the difference effects in each module. The topic of this work is to suggest a way to calculate the number and time instants for the rotations, and the optimal operation scheduling. This depends on several factors, such as the time instant for cleanings, the percentage of replacements, the quality of the feed water, etc. Due to the structure of the problem, the calculation is proposed to be done using genetic algorithms or Monte Carlo optimization.

Keywords: Reverse osmosis; Membrane module rotation; Operation scheduling; Membrane replacement

1. Introduction

Reverse osmosis (RO) technology has become the most important technique to produce drinkable water from brackish and sea water in regions where the water demand is higher than the available fresh water. There is likely to be a huge increase in the world desalination capacity in the near future. Estimations for the next five years predict the duplication of the current desalinated water capacity. So, an increasing effort for the improvement of the technology is now being carried out. Notice the work on the optimization of the operation [1–3], improvement of the energy recovery systems [4,5], advanced control of desalination plants [6,7], dynamic simulation [8], etc. The current document is focused on the optimization of the scheduling for membrane cleaning, partial replacement of the RO modules, and rotation of the modules inside each pressure vessel. See Lu et al. [9], Hu and Lu [10], for other approaches of the scheduling problem.

This document is organized as follows. Section 2 shows a general mathematical modeling of the RO membranes. Section 3 describes the modeling of the aging of the RO membranes, and the chemical cleaning, replacement and rotation of the modules.

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Next, Section 4 describes the optimization problem that is used for its resolution.

2. Modelling of the RO membranes

This section describes the mathematical model used in this document. Eqs. (1) and (2) show the water mass balance for feed and permeate streams respectively, where the z direction corresponds to the direction of the stream, from the inlet of the pressure vessel ($z = 0$) to the outlet of the pressure vessel ($z = L$).

$$\frac{\partial Q_f}{\partial z} = -h \cdot J_w \tag{1}$$

with $Q_f(0) = Q_{fo}/n_{pv}$ m^3/h

$$\frac{\partial Q_p}{\partial z} = +h \cdot J_w \tag{2}$$

with $Q_p(0) = 0\,\text{m}^3/\text{h}$.

where Q_f means the volumetric flow ratio at the feed side of the membrane, h means the cross-section width, Q_{fo} means the total feed flow of the RO train, n_{pv} means the number of pressure vessels of the RO train, Q_p means the volumetric flow ratio in the permeate side, J_w means the water flux that crosses the membrane, and L means the length of the pressure vessel. The L can be calculated as follows:

$$L = L_m \cdot n_m \tag{3}$$

where L_m means the length of one RO module and n_m means the number of RO modules in each pressure vessel.

The total permeate volumetric flow ratio produced in the RO train is calculated as follows:

$$Q_{ptotal} = Q_p|_{z=L} \cdot n_{pv} \tag{4}$$

Eqs. (5) and (6) show the salt mass balance for the feed and permeate side respectively.

$$\frac{\partial C_f}{\partial t} = \frac{1}{S_f} \cdot \frac{\partial (Q_f \cdot C_f)}{\partial z} - \frac{1}{h} \cdot J_s \tag{5}$$

with $C_f(z = 0) = C_{fo}\text{kg/m}^3$.

$$\frac{\partial C_r}{\partial t} = \frac{1}{S_r} \cdot \frac{\partial (Q_r \cdot C_r)}{\partial z} + \frac{1}{h} \cdot J_s \tag{6}$$

with $C_r(z = 0) = 0\,\text{kg/m}^3$.

where C_f and C_p mean the salt concentration of the feed flow and of the permeate flow, S_f and S_r mean the cross section for the feed and reject side, C_{f0} means the salt concentration of the feed stream, and J_w means the salt flux that crosses the membrane.

The water flux that crosses the membrane can be calculated as follows:

$$J_w = A \cdot (\Delta P(z) - \Delta\pi(z)) \tag{7}$$

where A means the hydraulic permeability of the membrane, ΔP means the pressure difference between both sides of the membrane, and $\Delta\pi$ means the osmotic pressure difference between both sides of the membrane.

Assuming atmospheric pressure in the permeate side, ΔP can be calculated as follows:

$$\Delta P(z) = P_f(z) - 1 \tag{8}$$

where P_f means the pressure in the feed side. It can be calculated as a function of the pressure drop, which is proportional to the feed flow, as follows:

$$\frac{\partial P_f}{\partial z} = -k_p \cdot (Q_f)^{ap} \tag{9}$$

with $P_f(z = 0) = P_{f0}$ bar.
where k_p and a_p are empirical parameters and P_{f0} means the pressure supplied by the high-pressure pump.

The osmotic pressure difference can be calculated by using the Morse equation:

$$\Delta\pi(z) = i \cdot \sigma \cdot \frac{R \cdot T}{\text{PM}} \cdot \Delta C_s(z) \tag{10}$$

where i means the van't Hoff factor, σ means the reflection coefficient, R means the gas constant, PM means the molecular weight of the salt, T means the temperature of the water, and ΔC_s means the difference between the salt concentration on the membrane surface on each side of the membrane as can be seen in Fig. 1, which corresponds to the salt gradient on both sides of the RO membrane.

$$\Delta C_s = C_{fm} - C_p \tag{11}$$

The C_{fm} cannot be measured, but it can be easily estimated by applying a mass balance in the direction of the water flux (J_w). The ratio between the salt concentration difference on the surfaces of the membranes and the bulks of the streams is called the polarization module and corresponds to the following equation:

$$\phi = \frac{\Delta C_s}{\Delta C} = \frac{C_{fm} - C_p}{C_f - C_p} \tag{12}$$

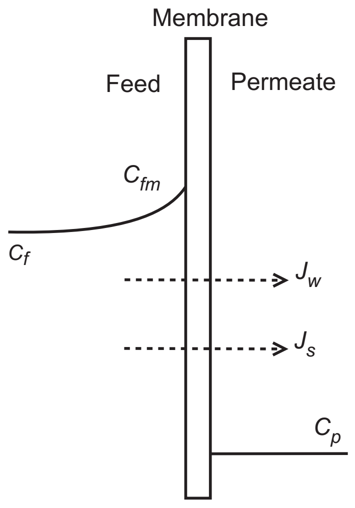


Fig. 1. Salt concentration gradient on both sides of the membrane.

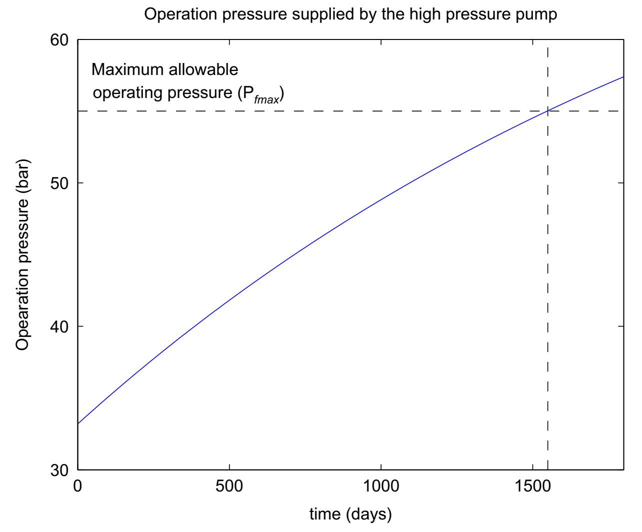


Fig. 2. Operation pressure. Maximum value of 55 bar exceeded after 1,550 days.

Taking Eq. (12) into account, the osmotic pressure can be calculated as follows:

$$\Delta\pi(z) = \phi \cdot i \cdot \sigma \cdot \frac{R \cdot T}{\mathrm{PM}} \cdot \Delta C(z) \tag{13}$$

Finally, the salt flux that crosses the membrane can be calculated as follows:

$$J_s = B \cdot \Delta C(z) \tag{14}$$

where B means the salt permeability of the membrane and ΔC means the salt concentration difference between both sides of the membrane.

A more exact mathematical model can be seen in Senthilmurugan et al. [11].

3. Modelling of the cleaning, replacement and rotation of the RO modules

Owing to the aging of the membrane, the hydraulic and salt permeability vary over time. On the one hand, the hydraulic permeability (A) decreases over time and a higher operation pressure is needed to keep the initial permeate flow. Fig. 2 shows a typical evolution of the operation pressure over five years. Notice that after 1,550 days, the required operation pressure has exceeded the maximum allowable pressure for the plant, which in the example case is 55 bar.

On the other hand, the salt permeability (B) increases over time and more salt particles are able to cross the membrane. Fig. 3 shows a typical evolution of the salt concentration in the permeate flow. Notice that after 1,350 days, the salt concentration has exceeded the maximum allowable salt concentration, which in the example case is 300 ppm.

Hydraulic permeability is modeled as follows (see Lu et al. [9]). It is divided into several factors, as can be seen in Eq. (15).

$$A = A_0 \cdot A_{\mathrm{i}} \cdot A_{\mathrm{r}} \tag{15}$$

where A_0 means the initial hydraulic permeability at the beginning of the operation, A_{i} embraces the irre-

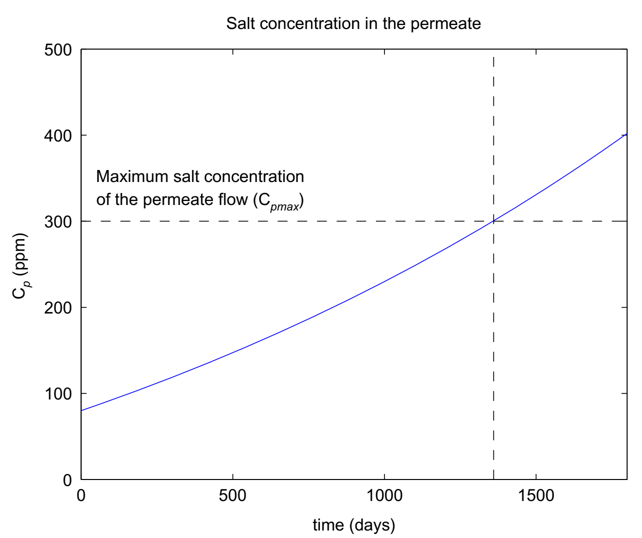


Fig. 3. Salt concentration of the permeate flow. Maximum value of 300 ppm exceeded after 1,350 days.

versible aging of the membrane, which can be reset only by the replacement of the RO module, and A_r embraces the reversible fouling, which can be eliminated by chemical cleanings. Both factors can be calculated as follows:

$$A_i = 1 - \Psi_A \cdot (t - t_{RP}) \quad (16)$$

$$A_r = \exp\left(-\frac{t - t_{CL}}{\Gamma_A}\right) \quad (17)$$

where Ψ_A and Γ_A are empirical factors that depend on the characteristic of each desalination plant (see Lu et al. [9], to obtain some typical values), $t - t_{RP}$ means the time delay from the last replacement, and $t - t_{CL}$ means the time delay from the last chemical cleaning. A_0 has the units of A, while A_i and A_r are dimensionless. Initially, the value of A_i and A_r is 1 and decreases with time. A_i is reset after one replacement and A_r is reset after one replacement or one chemical cleaning.

Similar equations can be formulated for the salt permeability:

$$B = B_0 \cdot B_i \cdot B_r \quad (18)$$

$$B_i = 1 + \Psi_B \cdot (t - t_{RP}) \quad (19)$$

$$B_r = \exp\left(+\frac{t - t_{CL}}{\Gamma_B}\right) \quad (20)$$

where B_0 has the units of B and means the initial salt permeability at the beginning of the operation. The B_i and B_r are dimensionless. Initially, the value of B_i and B_r is 1 and increases with time. B_i is reset after one replacement and B_r is reset after one replacement or one chemical cleaning.

Figs. 4 and 5 show the evolution of A_i, B_i (Fig. 4), A_r and B_r (Fig. 5), during an operation time of five years. A chemical cleaning is done at 500 days, a replacement of 50% of the membrane modules is done at 1,000 days, and a replacement of 100% of the membrane modules is done at 1,500 days.

Total hydraulic and salt permeabilities are plotted, respectively, in Figs. 6 and 7.

On the first approximation, we can work with an average value of the fouling parameters (Ψ_A, Γ_A, Ψ_B, and Γ_B) for each pressure vessel. In this case, in order to model the partial replacement of the RO modules of each pressure vessel, Eqs. (16), (17), (19) and (20) can be written as follows:

$$A_i = 1 - \Psi_A \cdot t + x_A \quad (21)$$

$$B_i = 1 + \Psi_B \cdot t - x_B \quad (22)$$

$$A_r = y_A \cdot \exp\left(-\frac{t - t_{CL}}{\Gamma_A}\right) \quad (23)$$

$$B_r = y_B \cdot \exp\left(+\frac{t - t_{CL}}{\Gamma_B}\right) \quad (24)$$

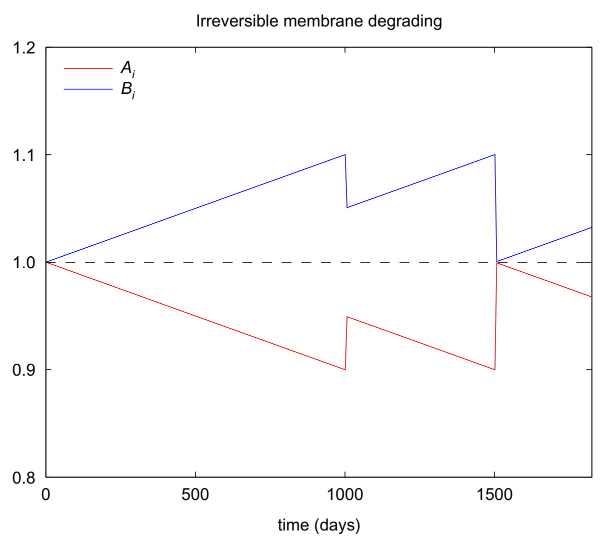


Fig. 4. Irreversible factor for the hydraulic and salt permeability.

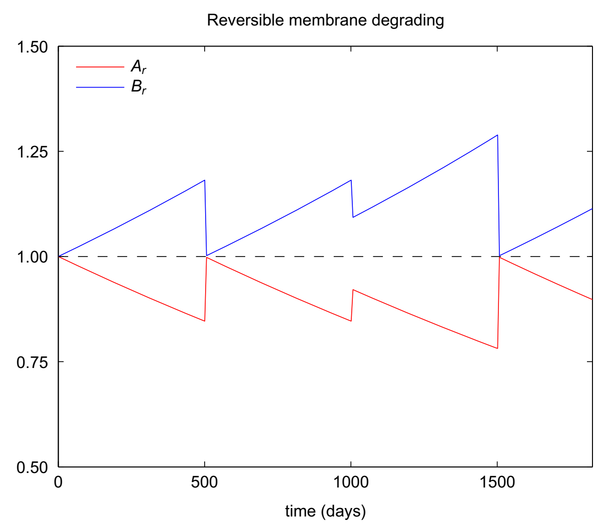


Fig. 5. Reversible factor for the hydraulic and salt permeabilities.

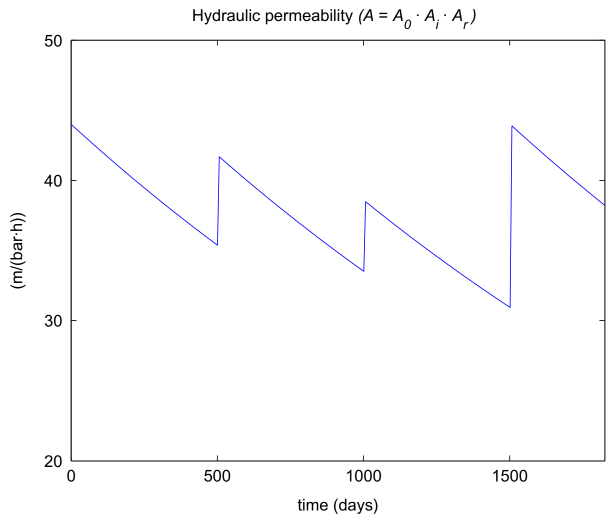


Fig. 6. Total hydraulic permeability over five years, with a chemical cleaning at 500 days, partial replacement at 1,000 days, and full replacement of the modules at 1,500 days.

where x_A, x_B, y_A and y_B are internal parameters of the modeling, which are calculated as follows:

$$x_{\mathrm{A}} = \begin{cases} t = 0 \rightarrow 0 \\ t = t_{\mathrm{RP}} \rightarrow x_{\mathrm{A}} + r \cdot (1 - A_{\mathrm{i}}) \end{cases} \tag{25}$$

$$x_{\mathrm{B}} = \begin{cases} t = 0 \rightarrow 0 \\ t = t_{\mathrm{RP}} \rightarrow x_{\mathrm{B}} + r \cdot (B_{\mathrm{i}} - 1) \end{cases} \tag{26}$$

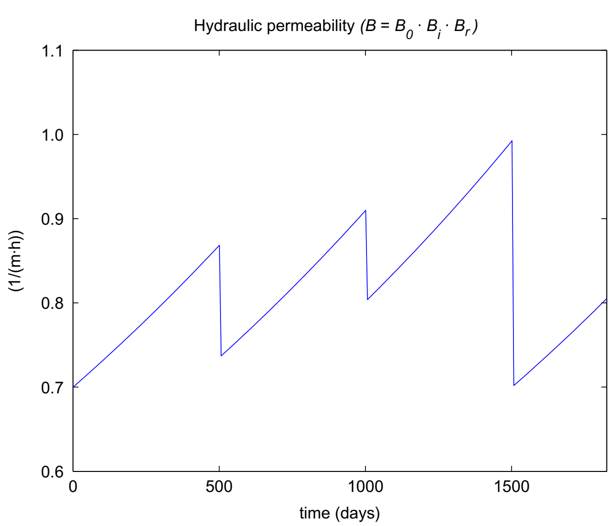


Fig. 7. Total salt permeability over five years, with a chemical cleaning at 500 days, partial replacement at 1,000 days, and full replacement of the modules at 1,500 days.

$$y_{\mathrm{A}} = \begin{cases} t = 0 \rightarrow 1 \\ t = t_{\mathrm{RP}} \rightarrow (1 - r) \cdot y_{\mathrm{A}} + r \cdot \exp\left(\frac{t - t_{\mathrm{CL}}}{\Gamma_{\mathrm{A}}}\right) \\ t = t_{\mathrm{CL}} \rightarrow 1 \end{cases} \tag{27}$$

$$y_{\mathrm{B}} = \begin{cases} t = 0 \rightarrow 1 \\ t = t_{\mathrm{RP}} \rightarrow (1 - r) \cdot y_{\mathrm{B}} + r \cdot \exp\left(-\frac{t - t_{\mathrm{CL}}}{\Gamma_{\mathrm{A}}}\right) \\ t = t_{\mathrm{CL}} \rightarrow 1 \end{cases} \tag{28}$$

where r means the percentage of RO modules that are replaced.

However, the fouling parameters depend on several factors, such as the salt concentration, operation pressure, flux, etc. Owing to this fact, these factors depend on the length of the pressure vessel; a better approximation requires working with different parameters for each RO module. Initially, we can assume a linear dependence with distance from the inlet (z), as follows:

$$\Psi_{\mathrm{A}}(z) = a_{\Psi_{\mathrm{A}}} + b_{\Psi_{\mathrm{A}}} \cdot z \tag{29}$$

$$\Psi_{\mathrm{B}}(z) = a_{\Psi_{\mathrm{B}}} + b_{\Psi_{\mathrm{B}}} \cdot z \tag{30}$$

$$\Gamma_{\mathrm{A}}(z) = a_{\Gamma_{\mathrm{A}}} + b_{\Gamma_{\mathrm{A}}} \cdot z \tag{31}$$

$$\Gamma_{\mathrm{B}}(z) = a_{\Gamma_{\mathrm{B}}} + b_{\Gamma_{\mathrm{B}}} \cdot z \tag{32}$$

where the parameters $a_{\Psi_{\mathrm{A}}}, b_{\Psi_{\mathrm{A}}}, \ldots,$ etc. should be calculated for each desalination plant.

4. Optimization problem

The objective of the optimization problem is to calculate the optimal scheduling for replacement, chemical cleaning and module rotation over a period of several years. The manipulated variables are shown as follows:

- Number of chemical cleanings, n_{CL}.
- Time instant of the chemical cleanings, $t_{\mathrm{CL}}[1, 2, 3 \ldots n_{\mathrm{CL}}]$.
- Number of replacement, n_{RP}.
- Time instant of the replacement, $t_{\mathrm{RP}}[1, 2, 3 \ldots n_{\mathrm{RP}}]$.
- Percentage of each replacement, $r[1, 2, 3 \ldots n_{\mathrm{RP}}]$.
- Number of module rotation, n_{ROT}.
- Time instant of the module rotation, $t_{\mathrm{ROT}}[1, 2, 3 \ldots n_{\mathrm{ROT}}]$.

Mathematically, the problem can be formulated as a minimization of an objective function, which depends on the operation cost, as follows:

$$C = \$_{\mathrm{CL}} \cdot n_{\mathrm{pv}} \cdot n_{\mathrm{m}} \cdot n_{\mathrm{CL}} + \sum_{i=1}^{n_{\mathrm{RP}}} \$_{\mathrm{RP}} \cdot n_{\mathrm{pv}} \cdot n_{\mathrm{m}} \cdot r[i] + \int_0^{\tau=5\ \mathrm{years}} \$_{\mathrm{P}} \frac{Q_{\mathrm{f0}}(\tau) \cdot P_{\mathrm{f}}(\tau)}{\eta} \mathrm{d}\tau \tag{33}$$

where C means the operation cost, $\$_{\mathrm{CL}}$ means the cost of one chemical cleaning, $\$_{\mathrm{RP}}$ means the cost of the replacement of all RO modules, $\$_{\mathrm{P}}$ means the cost of the operation, η means the high pressure pump efficiency, Q_{f0} means the feed volumetric flow, and P_{f} means the operation pressure, which is supplied by the high-pressure pump. Notice that Q_{f0} and P_{f} depend on the aging of the membrane.

$$Q_{\mathrm{f0}} = f_1(A(t), B(t)) \tag{34}$$

$$P_{\mathrm{f}} = f_2(A(t), B(t)) \tag{35}$$

Besides, several constraints should be taken into account. The operation pressure should not exceed a maximum value (P_{fmax}) for security reasons, as can be seen in Fig. 2, and the concentration of the permeate flow should not exceed a maximum value, (C_{pmax}), for water consumption, as can be seen in Fig. 3.

$$P_{\mathrm{f0}} < P_{\mathrm{fmax}} \tag{36}$$

$$C_{\mathrm{p}}(z = L) < C_{\mathrm{pmax}} \tag{37}$$

This optimization problem consists of a mixed-integer nonlinear programming (MINLP) problem. The complexity of the problem requires that its solution should be found using advanced algorithms for optimization. For example, the problem can be solved using genetic algorithms or Monte Carlo optimization.

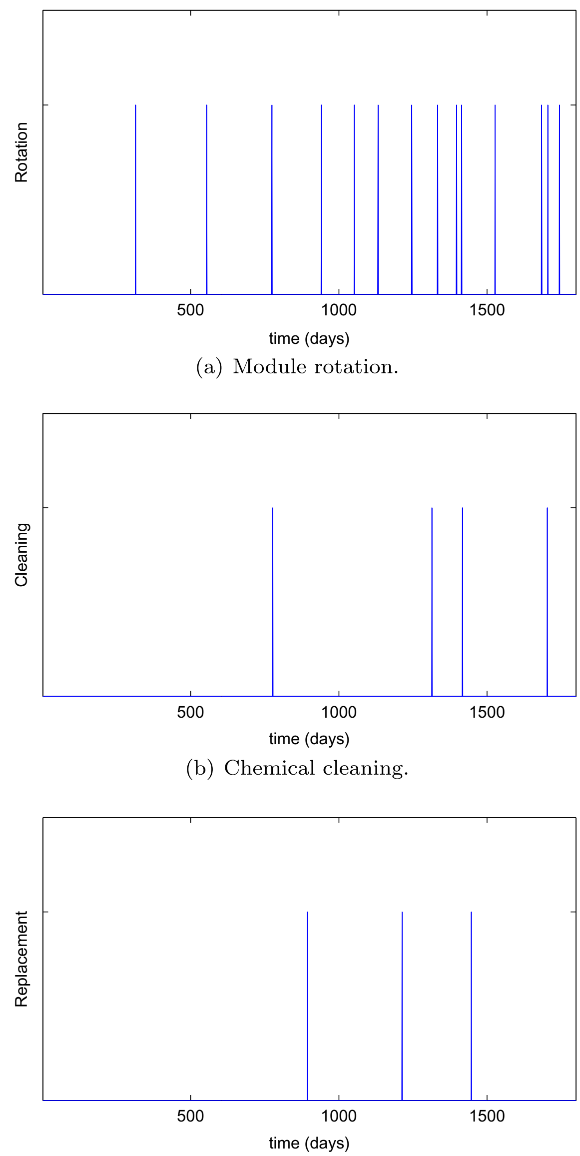
Assuming that we know the value of the empirical parameters of Eq. (29), the optimization problem can be solved. Fig. 8 shows an example of the resolution of the optimization problem, where the value of the parameters of Eq. (29) has been fixed. The optimization was solved numerically using Matlab.

5. Future work

The future work embraces the estimation of the parameters of Eq. (29), using a pilot desalination plant, and then the optimization of the operation scheduling. In order to simplify the optimization problem, it is a good idea to make the partial replacement coincide with the module rotation. Finally, to reduce labor costs, module rotation can be replaced with the automatic change of the direction of the feed flow.

6. Conclusions

This paper has presented a methodology to estimate the optimal scheduling of RO plants, that considers chemical cleaning, membrane replacement, and rotation. First, it has been described how the effect of chemical cleaning and replacement can be mathematically included into a standard model of RO membranes. Next, based on this model, a MINLP optimization problem has been presented for the calculation of the optimal scheduling of the operation of a desalination plant over several years. Owing to the



(a) Module rotation.
(b) Chemical cleaning.
(c) Module replacement.

Fig. 8. Example of the scheduling operation, with the time instant for module rotation, chemical cleaning, and replacement, during 5-year-long operation.

complexity of the problem, it can be solved using genetic algorithms. Future work embraces the estimation of the required empirical parameters, using a pilot desalination plant.

List of symbols

A — hydraulic permeability of the membrane, m/h bar
A_0 — initial value of A, m/h bar
A_i — irreversible part of (A,) (-)
A_r — reversible part of A, (-)
a_p — empirical parameter for the pressure drop calculation, (-)
a_{Γ_A} — empirical parameter for the Γ_A calculation, days
a_{Γ_B} — empirical parameter for the Γ_B calculation, days
a_{Ψ_A} — empirical parameter for the Ψ_A calculation, days
a_{Ψ_B} — empirical parameter for the Ψ_B calculation, days
B — salt permeability of the membrane, 1/m h
B_0 — initial value of B, 1/m h
B_i — irreversible part of B, (-)
B_r — reversible part of B, (-)
b_{Γ_A} — empirical parameter for the Γ_A calculation, days
b_{Γ_B} — empirical parameter for the Γ_B calculation, days
b_{Ψ_A} — empirical parameter for the Ψ_A calculation, days
b_{Ψ_B} — empirical parameter for the Ψ_B calculation, days
C — operation cost, $
C_f — salt concentration of the feed flow, kg/m^3
C_{f0} — salt concentration of the feed stream at the inlet of the RO train, kg/m^3
C_p — salt concentration of the permeate flow, kg/m^3
C_{pmax} — maximum salt concentration for drinkable water, kg/m^3
h — cross section width, m
i — van't Hoff factor, (-)
J_w — water flux that crosses the membrane, m/h
J_s — salt flux that crosses the membrane, $kg/(m^2 h)$
k_p — empirical parameter for the pressure drop calculation, $bar/(m^3 h)^{ap}$
L_m — length of each RO module, m
L — length of each pressure vessel, m
n_m — number of RO modules in each pressure vessel, (-)
n_{pv} — number of pressure vessels in the RO train, (-)
P_f — pressure of the feed flow, bar
P_{fmax} — maximum operation pressure, bar
PM — salt molecular weight, kg/kmol
Q_f — volumetric flow ratio in the feed side of the membrane, m^3/h
Q_{f0} — feed volumetric flow ratio of the RO train, m^3/h
Q_p — volumetric flow ratio in the permeate side of the membrane, m^3/h
r — percentage of modules that are replaced, (-)
R — gas constant, $(bar\, m^3)/(kmol\, K)$
S_f — cross section of the feed side, m^2
S_p — cross section of the permeate side, m^2
T — temperature, K
σ — reflection coefficient, (-)
ϕ — polarization module, (-)
ΔP — pressure difference between both sides of the membrane, bar
$\Delta\pi$ — osmotic pressure difference between both sides of the membrane, bar
Γ_A — fouling parameter for hydraulic permeability, days
Γ_B — fouling parameter for salt permeability, days
Ψ_A — fouling parameter for hydraulic permeability, days
Ψ_B — fouling parameter for salt permeability, days
$\$_{CL}$ — cost of one chemical cleaning, $
$\$_{RP}$ — cost of the replacement of all RO modules, $
$\$_P$ — pumping cost, $/kW

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References

[1] T. Manth, M. Gabor, E. Okleajas, Minimizing RO energy consumption under variable conditions of operation, Desalination 157 (2003) 9–21.
[2] L.G. Palacin, F. Tadeo, C. de Prada, H. Elfil, J. Salazar, Operation of desalination plants using hybrid control, Desalin. Water Treat. 25 (2011) 119–126.
[3] J. Salazar, F. Tadeo, C. de Prada, Control system for reverse osmosis plants (RO) and renewable energy generation, in: International Conference on Renewable Energies and Power Quality, Granada, Spain, 2010.
[4] S.A. Avlonitis, Energy consumption and membrane replacement cost for seawater RO desalination plants, Desalination 157 (2003) 151–158.
[5] R.L. Stover, Development of a fourth generation energy recovery device, Desalination 165 (2004) 313–321.

[6] C. McFall, A. Bartman, P.D. Christofides, Y. Cohen, Control and monitoring of a high-recovery reverse-osmosis desalination process, Eng. Chem. 47 (2008) 6698–6710.
[7] A. Bartman, C. McFall, P.D. Christofides, Y. Cohen, Model predictive control of feed flow reversal in a reverse osmosis desalination process, Proc. Control 19 (2009) 433–442.
[8] L.G. Palacin, F. Tadeo, H. Elfil, C. de Prada, J. Salazar, New dynamic library of reverse osmosis plants with fault simulation, Desalin. Water Treat. 25 (2011) 119–126.
[9] Y. Lu, Y. Hu, D. Xu, L. Wu, Optimum design of reverse osmosis seawater desalination system considering membrane cleaning and replacing, J. Membr. Sci. 282 (2006) 7–13.
[10] Y. Hu, Y. Lu, Cleaning strategy of the membrane modules in the reverse osmosis seawater desalination system, J. Chem. Indus. Eng. 56 (2005) 499–505.
[11] S. Senthilmurugan, A. Ahluwalia, S. Gupta, Modeling of a spiral-wound module and estimation of model parameters using numerical techniques, Desalination 176 (2005) 269–286.