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Techno-economic optimization of SWRO desalination using advanced control approaches

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ABSTRACT

This paper presents two advanced control techniques that can be used to optimize the operation of seawater reverse osmosis (SWRO) desalination plants to decrease the production cost. The first technique uses the model predictive control (MPC) controller to operate the plant at its optimum operating conditions, while the second technique is based on early detection of membrane fouling. The objective of this work is to compare the SWRO desalination plant optimized performance with the conventional operation and evaluate the optimization effect on the unit production cost as well as conduct adequate economical analysis. Three case studies including three existing SWRO plants were tried and compared using the above technique. The second technique proved to be effective and the results were compared with the existing data and proved to be satisfactory.

Keywords: Desalination; Optimization; Advanced process control; Economic analysis

1. Introduction

In recent years, while the costs of producing fresh water from SWRO desalination have become more comparable to the other desalination technologies, costs are still considered as a limiting factor for widespread application of this technology. In order to decrease the production cost, process control and cost optimization have become increasingly evident [1]. The performance of RO plants is quite sensitive to the quality of the feed and plant operating conditions. This means that an RO plant requires a very efficient pretreatment process and an accurate control system to maintain its operation close to the optimum conditions. This may result in increased productivity and prolongs the life of the membranes due to the reduction of membrane fouling conditions [2].

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Feed seawater temperature and membrane fouling are most critical disturbances that have strong effect on the SWRO process. The control system in conventional RO plant operation tends to keep the flow and thus the recovery constant at the design value. Any change in the membrane flux, e.g. by temperature or fouling, is compensated by adjusting the feed pressure to a pre-designed value. If the actual feed pressure is maintained constant throughout the year, the product flow rate will vary and hence the system will not work under the optimum operating conditions. Then the use of advanced controllers would enable the plant to run at the optimum conditions throughout the year thus and hence allowing a reduction in operating expenses [2].

Membrane fouling is one of the most critical disturbances that have strong effect on SWRO process operation. Providing a fouling detector tool allows the discovery of any fouling or scaling development on the

RO membranes in early real times, thus to take immediate corrective measures before it is too late.

Fouling detector concept is any recently early warning alarm software system and its supplementary equipment that satisfies affordable, reproducible, reliable and simple operation. Saad [3] proposed an early fouling detector software that can be used to optimize a membrane system. On the other hand, the life span of an SWRO membrane has a significant impact on the operating cost. The expected life of an SWRO membrane element is 2–5 years [4].

The annual operating cost contribution associated with membrane element replacement will vary in a wide range depending on the plant capacity (i.e. the number of membrane elements in an RO plant). Maximization of SWRO membrane elements life is essential to the operating cost. Consequently, the use of advanced strategy that controls the membrane fouling in SWRO plants by early detection of it to take the correct action before its accumulation on the membranes surface will result in increasing the membrane life span: furthermore, higher plant availability and lower operating cost.

Few studies have considered the control of RO desalination processes using conventional and advanced controls. Their results can be concluded as follows:

SWRO plant operation is more difficult to control than other types of desalination plants due to its operating parameters nature and overlap [5]. The common control system in SWRO plants is based on the programmable logic controller (PLC), particularly when provided with supervisory control and data acquisition (SCADA) system [6]. The use of advanced techniques such as neural networks, fuzzy logic and artificial intelligence in RO desalination plant control have been studied by some researchers without any clear results about their practical viability [7,8]. One advanced control strategy that has gained acceptance in industry is model predictive control (MPC) [9]. It was used in an RO process by Burden et al. [10], Assef et al. [11] and Deshpande et al. [12].

This paper presents the evaluation of two optimization approaches from techno-economic points of view. The first one is based on an MPC controller to adjust the plant to operate at optimum feed pressure and compensate the effect of feed temperature disturbance as shown in Fig. 1. The second one is based on using fouling detectors to control membrane chemical cleaning time to be early as a correction action against fouling accumulation disturbance (Fig. 2).

2. RO operating parameters model

The model used is that for spiral-type SU-820, Toray RO element [13]. The transport equations of the water flux, J_V, and salt flux, J_S, through RO membranes based on the non-equilibrium thermodynamics are given below [14]:

$$J_v = L_P \left\{ \Delta P - \sigma \left[\pi(C_M) - \pi(C_p) \right] \right\} \tag{1}$$

$$J_s = P(C_M - C_p) + (1-\sigma)\bar{C}_S \cdot J_v \tag{2}$$

where L_p is a solution permeability, P a salt permeability and σ a reflection coefficient, π is the osmotic pressure, C_M is the salt concentration at the membrane surface, C_p is the permeate concentration and $\bar{C}_S$ is the average concentration. L_p, P and σ are membrane transport parameters that specify membrane properties. For high rejection membranes, over 99%, σ is approximately 1 and Eq. (2) can be simplified to become:

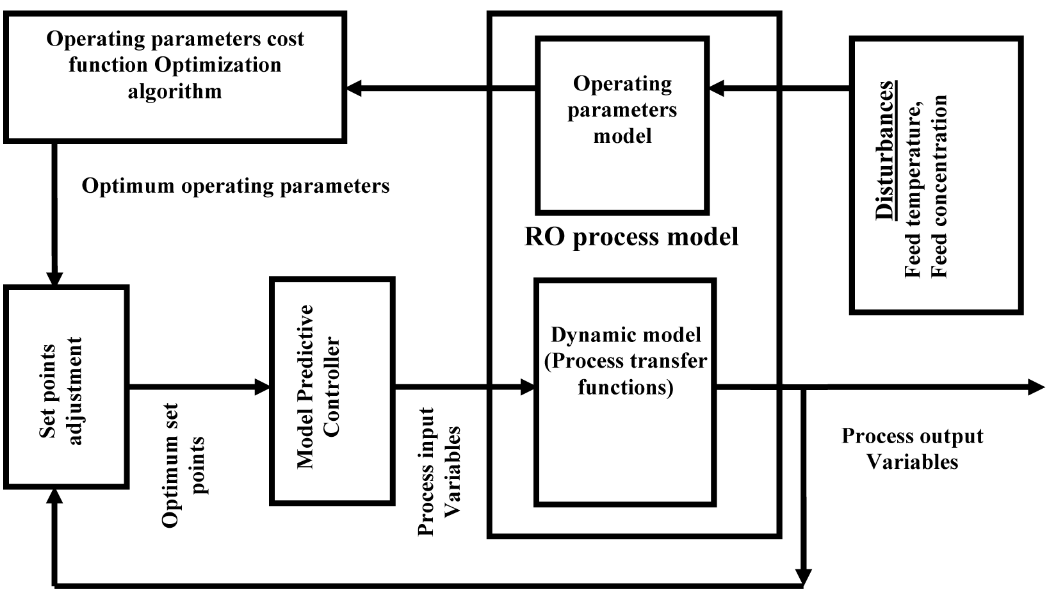

Fig. 1. Optimization approach based on MPC control.

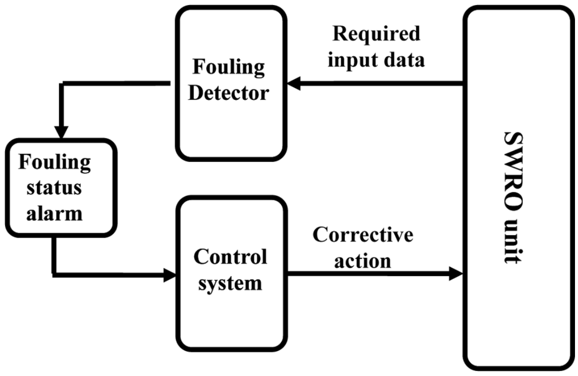

Fig. 2. Fouling detector optimization approach.

$$J_S = P \cdot (C_M - C_p) \tag{3}$$

C_p is also given by

$$C_P = \frac{J_S}{J_V} \tag{4}$$

The balance of mass transfer across the membrane gives rise to the following equation:

$$\frac{C_M - C_P}{C_B - C_P} = \exp\left(\frac{J_V}{k}\right), \quad k = \frac{D}{\delta} \tag{5}$$

where k is a mass transfer coefficient, C_B is the bulk concentration, D is the diffusivity and δ is a boundary layer thickness.

The correlation used for evaluating the mass transfer coefficient, k, is given by the following equation [14]:

$$\mathrm{Sh} = a \cdot \mathrm{Re}^{0.875} \cdot \mathrm{Sc}^{0.25} \tag{6}$$

where Sh = kd/D is the Sherwood number, a is constant = 0.08, the Reynolds number Re = $\rho ud/\eta$ = 100, the Schmidt number Sc = η/D, u is the flow velocity and d is a hydraulic diameter of the feed water channel. The osmotic pressure (π, Pa) is given by the following equation [14]:

$$\pi(C,T) = (0.6955 + 0.0025T) \times 10^8 \frac{C}{roh} \tag{7}$$

where C is the salt concentration in kg/m^3 and T the temperature in °C. For the density of seawater (roh, kg/m^3):

$$roh = 498.4m + \sqrt{\frac{2484m^2}{10^{-2}} + 752.4mC} \tag{8}$$

$$m = 1.0069 - 2.757 \times 10^{-4} T \tag{9}$$

For the viscosity of seawater (η, Pa.s),

$$\eta = \frac{1.234}{10^6} \exp\left(\frac{212 \times C}{10^5} + \frac{1965}{273.15 + T}\right) \tag{10}$$

For the diffusivity (D, m^2/s),

$$D = \frac{6.725}{10^6} \exp\left(\frac{0.1546 \times C}{10^3} - \frac{2513}{273.15 + T}\right) \tag{11}$$

The membrane element used is of the spiral-wound type having the dimensions $w = 1$ m, $h = 6$ m and $d = 2$ mm. Membrane type material is cross linked fully aromatic polyamide composite, the membrane parameters at standard operating conditions (T_f = 25°C and P_f = 5.5 MPa) are $L_p = (2.52)10^{-12}$ m^3/m^2 Pa s and $P = (12.1)10^{-9}$ m/s [1].

The model used takes into consideration both temperature and pressure effects on the membrane parameters themselves as the following relations the temperature effects are:

$$\frac{L_{PT}}{L_p} = \exp\left[0.0093(T - 25)\right] \tag{12}$$

$$\frac{P_T}{P} = \exp\left[0.0483(T - 25)\right] \tag{13}$$

The pressure effects are:

$$\frac{L_{Pp}}{L} = \exp\left[-0.064\left(\Delta p \times 10^{-6} - 5.5\right)\right] \tag{14}$$

$$\frac{P_p}{P} = \exp\left[0.073\left(\Delta p \times 10^{-6} - 5.5\right)\right] \tag{15}$$

MATLAB m-file program was developed to estimate the properties of the RO plant at different operating conditions. The input data is membrane parameters L_p, P, feed seawater temperature T_f and concentration C_f. The feed pressure, P_f is fixed, the program estimates the fluxes of salt and water for membrane and evaluate the product concentration, C_p and recovery, R. Results are compared with the results calculated by using a membrane element manufacturer software called CAROL®. As demonstrated in Figs. 3 and 4, the product concentration is quite sensitive to both feed temperature T_f and feed concentration C_f; increasing either of them results in a substantial increase in C_p.

The feed pressure, however, has the opposite effect, i.e., increasing the feed pressure decreases the product water concentration. The effect of T_f, C_f and P_f on the recovery R (defined as the ratio between permeate (product) water flow rate and feed water flow rate) of the RO membrane element is demonstrated in Figs. 5 and 6. It can be seen that the increase in feed water temperature for a given value of feed concentration causes an increase in the water recovery. The recovery levels are higher for lower feed concentration than for higher concentration. The effect of the feed pressure is an increase in the recovery.

3. Optimizing SWRO operating cost estimation model

Cost estimation model (CEM) is necessary for applying different mathematical optimization algorithms to estimate the optimum SWRO process operating pa-

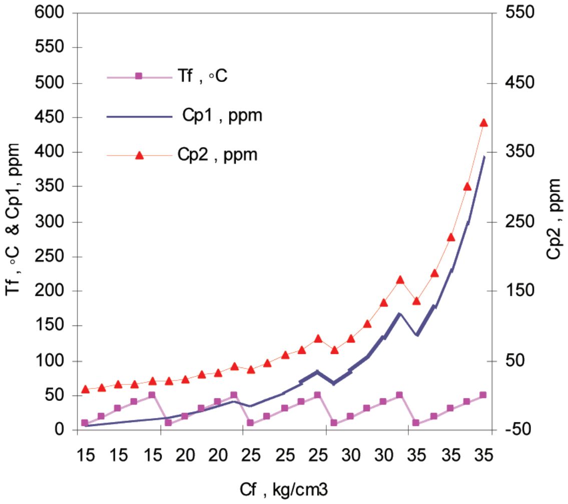

Fig. 3. Effect of feed concentration and temperature on Permeate concentration [(1) simulated, (2) calculated by CAROL] at constant feed pressure.

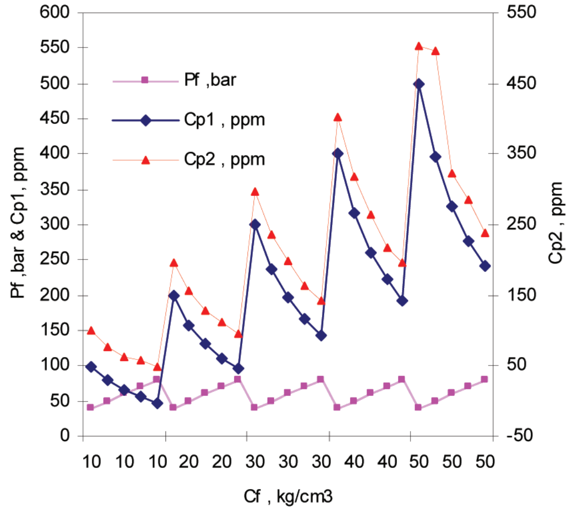

Fig. 4. Effect of feed concentration and pressure on permeate concentration [(1) simulated, (2) calculated by CAROL] at constant feed temperature.

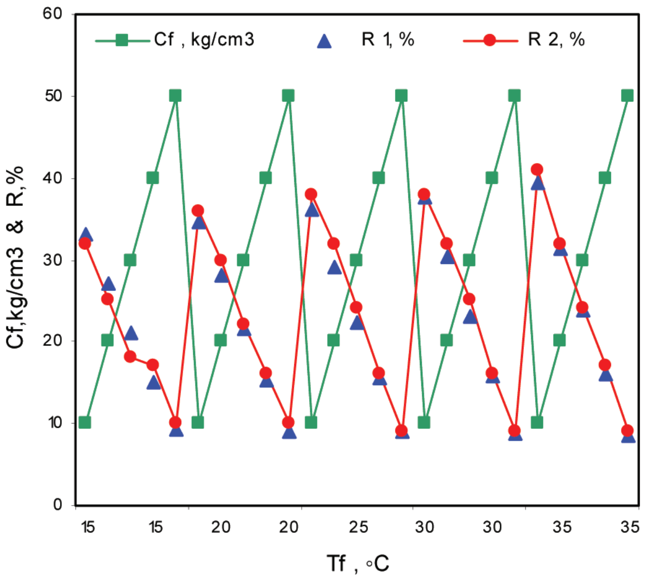

Fig. 5. Effect of feed concentration and temperature on overall recovery ratio [(1) simulated, (2) calculated by CAROL] at constant feed pressure.

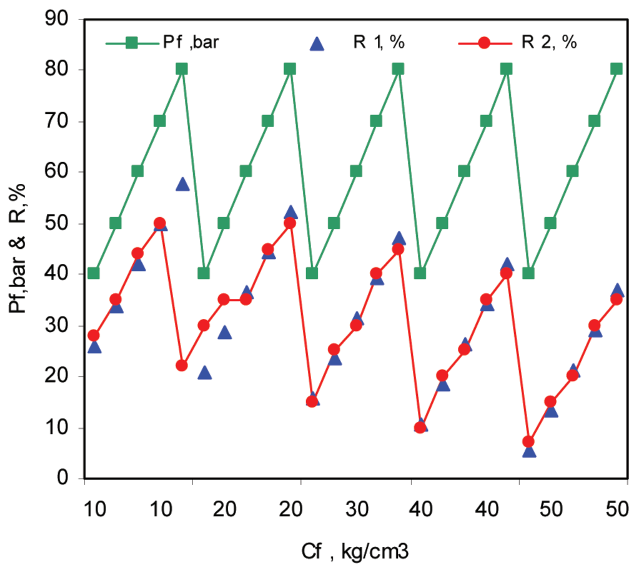

Fig. 6. Effect of feed concentration and pressure on overall recovery ratio [(1) simulated, (2) calculated by CAROL] at constant feed temperature.

rameters. Empirical relationships to determine the costs of components are obtained from previously developed CEMs [15,21]. Recently CEMs considered the effective operating variables are P_f, T_f and C_f.

The feed water flow rate was assumed constant; the percentage recovery and product concentration C_p in ppm of the RO system can be estimated in terms of these three variables as [2]:

$$R = -6.609\times10^{-2} - 1.239\times10^{-2} C_f + 9.209\times10^{-2} P_f + 8.38\times10^{-3} T_f \quad (16)$$

$$C_p = 156.728 + 8.27541 C_f - 72.3046 P_f + 8.36 T_f \quad (17)$$

where P_f (MPa) is the feed pressure, T_f (°C) is the feed temperature and C_f (kg/m³) is feed water salt concentration. The operating CEM, (cost electricity and chemicals per unit product water (C_w, \$/m³) to be optimized was expressed in terms of the three mentioned main operating variables as:

$$C_w = 0.643392 + 3.96\times10^{-2} C_f - 0.206595 P_f - 7.89\times10^{-2} T_f + 6.826\times10^{-4} C_f T_f + 1.41\times10^{-2} P_f T_f - 2.12\times10^{-4} C_f P_f T_f \quad (18)$$

To show the influence of operating variables on the specific water cost of SWRO plant, another MATLAB m-file was prepared to simulate the mentioned CEM.

The results show that high feed water concentration (at constant $T_f = 25°C$) increasing the feed water pressure results in a decrease of the specific water cost.

At low C_f, increasing the pressure causes a smaller cost decrease. Increasing C_f while maintaining a constant P_f results in an increase in water cost, with more increasing at lower feed pressure than at higher pressure (Fig. 7). This trend creates from the fact that for a particular C_f and membrane area installed in the system, increasing P_f results in a higher product water recovery.

Fig. 8 shows the influence of feed water temperature and concentration on the specific water cost for a constant operating pressure of 6.0 MPa. It can be seen that increasing the feed water temperature results in a drop in the specific water cost due to the increase in membrane flux and the associated increase in the plant water recovery.

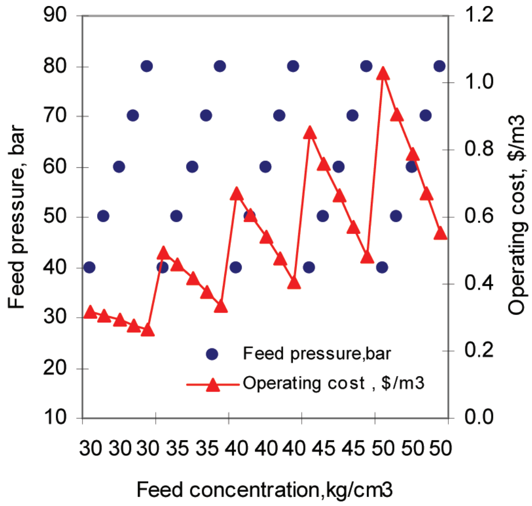

Fig. 7. Operating cost vs. feed concentration and pressure at constant feed temperature.

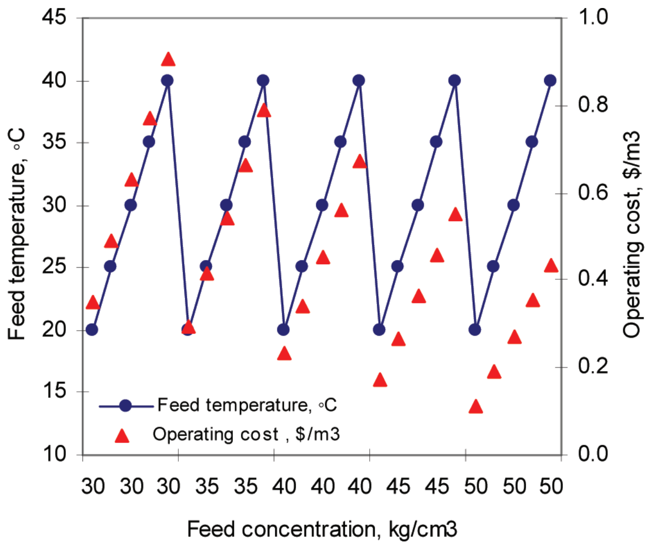

Fig. 8. Effect of feed water temperature and concentration on the specific water cost at a constant operating pressure.

Consequently, the optimization effort is focused on *minimizing* C_w subjected to the following operating variables constraints:

$$\begin{aligned} &4 \le P_f \le 8 && \text{MPa} \\ &15 \le T_f \le 40 && °\text{C} \\ &35 \le C_f \le 50 && \text{kg/m}^3 \end{aligned} \tag{19}$$

This optimization trend had been performed using MATLAB Optimization Toolbox [16].

4. Optimizing membrane performance

Optimization of membrane system by fouling control is an important issue with respect to membrane life time [22].

Performance normalization is a standard approach for fouling detection in RO system equipped with PLC. This normalization performance is a current industry standard performance analysis and evaluation technique which is based on RO flux decline characteristics of membranes via normalizing system operating data in accordance with ASTM D-4516 standard method. This method is based on a large amount of operating data over a long period of time to establish a definite trend which is virtually impossible [3]. So, to detect the early development of membrane fouling in a system it is not a simple and accurate process.

The fouling detector section being addressed here is any recently early warning alarm software system and its supplementary equipments that satisfy affordable, reproducible, reliable and simple (i.e., requires low or minimum operator understanding and training), such that ''CATRON'' licensed by TORAY membranes manufactures, ''Silent alarm'' licensed by MASAR Technologies and other advanced soft ware.

Akgul et al. [4] have recently suggested that operating costs decrease linearly 5% with increasing the membrane life from 3 to 5 years as shown in Fig. 9. So, if an appropriate fouling detector is used, it is acceptable to assume that the membrane life will increase at least 1 year if compared to operations in the case of no fouling control. Consequently, operating cost could be optimized and decrease by 2.5%.

5. Economic analysis

5.1. Economic analysis parameters

Economic analysis consideration is that most effective factor that determines the applicability of such optimi-

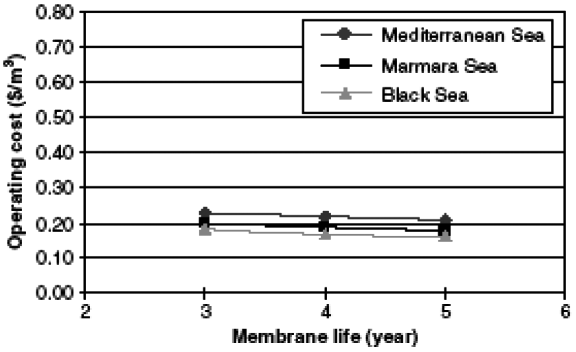

Fig. 9. Effect of membrane life on operating cost from [4].

zation approach. This analysis based on evaluation the following parameters:

5.1.1. Added cost

The per unit added cost due to installation optimization equipments (Θ, \$/m^3) is associated with capital and operating expenses. it can be estimated from the following relation:

$$\Theta = \frac{i \times (1+i)^n}{(1+i)^n - 1} \times \frac{\mathrm{CC}}{\mathrm{PDP} \times (\mathrm{PAV}) \times (365)} + \frac{\mathrm{OC}}{\mathrm{PDP} \times (\mathrm{PAV}) \times (365)} \tag{20}$$

where CC is capital cost of optimization equipment in \$, OC is operating cost of optimization equipment in \$/y, i is the interest rate (equal to 8%), n is number of years remaining in lifetime of desalination plant, years PDP is nominal plant daily production, m^3/d PAV is plant availability (taken equal to 0.9).

5.1.2. Saving (economic benefit)

As a result of using optimization techniques, per unit saving (Ψ, \$/m^3), can be estimated from the following relation:

$$\Psi = \%\mathrm{SAV} \times \mathrm{UC} \tag{21}$$

where %SAV is a percentage saving result of using optimization techniques, UC is the conventional unit price of plant product water, (\$/m^3). The percentage saving that can be achieved by optimizing operation with advanced control can be expressed as:

$$\%\mathrm{SAV} = \frac{\mathrm{UC} - \mathrm{UC}_{\mathrm{opt}}}{\mathrm{UC}_{\mathrm{opt}}} \times 100 \tag{22}$$

where $\mathrm{UC}_{\mathrm{opt}}$ = price of 1 m^3 of product water due optimizing plan operation with advanced control approach, (\$/m^3).

5.1.3. Net added cost

The per unit net added cost (Δ, \$/m^3) which is defined as the different between per unit added cost and per unit saving is an important indicator for estimating the applicability of considered optimization approach. Positive Δ indicates a non-feasible situation while a negative indicates a feasible one. It can be estimated from the following relation:

$$\Delta = \Theta - \Psi \tag{23}$$

5.2. Evaluation of general case economical parameters

On the basis of SWRO plant specification, MPC and fouling detector cost shares given in Table 1 [2–4], general case economic analysis parameters are calculated and graphically represented.

For installation of fouling detector, as shown in Fig. 10, added cost decreases with increasing both of n (i.e. old plant required more cost than the new one) and the SWRO plant size (capacity) ranging from 0.012 to 0.021 \$/m^3

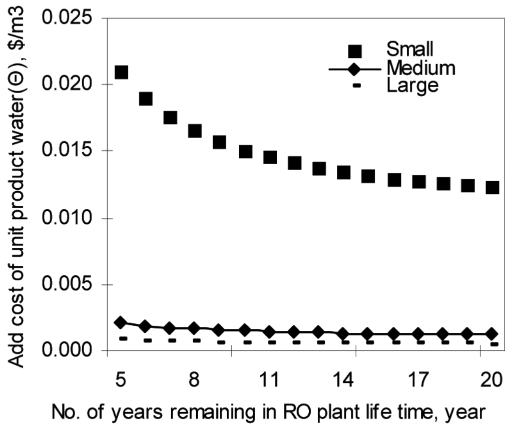

Fig. 10. Relation between added cost results of installing fouling detector and plant life time.

Table 1
Estimated SWRO plants specifications and optimization technique economics

	SWRO plant		
Size	Small	Medium	Large
Capacity, m^3/d	400	400–10000	>10000
Unit cost, \$/m^3	1.6	1.25	0.7
Fouling detector			
% SAV		2.5	
Capital cost, ×10^3, \$		7750	
Operation cost, \$/y		775	
MPC			
% SAV		10	
Capital cost, ×10^3, \$	430	647	862.6
Operation cost, ×10^3 \$/y		39	52

for small SWRO plant size, from 0.0012 to 0.0021 $/m^3 and from 0.0005 to 0.0008 $/m^3 for medium and large SWRO plant sizes respectively.

As shown in Fig. 11, saving increases with increasing *n* and with the SWRO plant size decreasing. It ranges from 0.094 to 0.376 $/m^3 for small SWRO plant size, from 0.073 to 0.29 $/m^3 and from 0.041 to 0.16 $/m^3 for medium and large plant sizes respectively. Installation fouling detector net added cost increases negatively with increasing years remaining and with the SWRO plant size decreasing as shown Fig. 12. It ranges from negative 0.07 to 0.36 $/m^3 for small SWRO plant size, from 0.07 to 0.29 $/m^3 and from 0.04 to 0.16 $/m^3 for medium and large SWRO plant sizes respectively, it exhibits negative values for all plant sizes indicating that the installation of fouling detector in these plants can result a net reduction in the cost of water.

Fig. 13 shows that added cost due to installation of MPC decreases with the increasing both *n* and plant size. It ranges from 0.65 to 1.2 $/m^3 for small plant size, from 0.1 to 0.15 $/m^3 and from 0.05 to 0.08 $/m^3 for medium and large SWRO plant sizes respectively.

Fig. 14 shows that saving increases with increasing *n* and decreasing the plant size. It ranges from 0.001 to 0.0041 $/m^3 for small plant size, from 0.0008 to 0.0032 $/m^3 and from 0.0004 to 0.0017 $/m^3 for medium and large sizes respectively. Fig. 15 shows that net added cost decreases with increasing both of *n* and plant size. It ranges from positive 1.1 to 0.6 $/m^3 for small plant size, from 0.15 to 0.084 $/m^3 and from 0.086 to 0.049 $/m^3 for medium and large sizes respectively. It depicts the variation of net added cost with *n* for different plant sizes and exhibits a positive value for all plant sizes. Although Fig. 15 indicates that installation of MPC in these plants cannot give a net reduction in the cost of water which means no feasibility situation from economic considerations point of view.

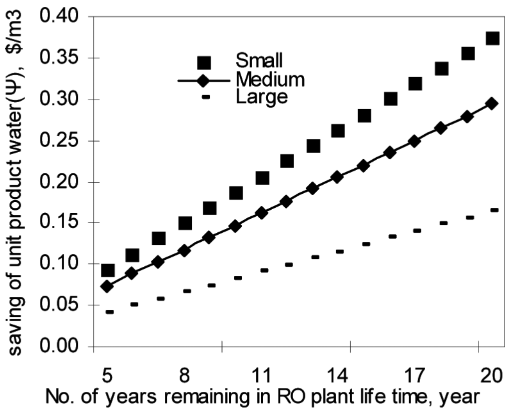

Fig. 11. Relation between fouling detector saving and plant life time.

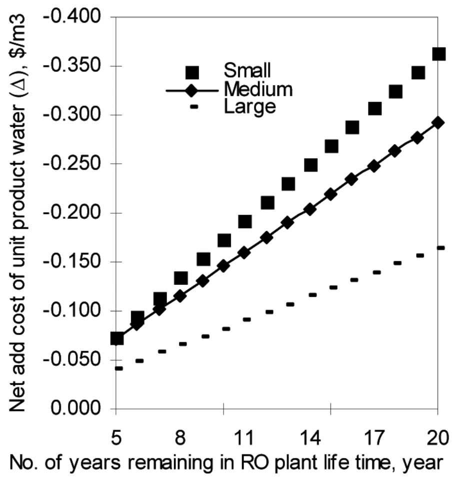

Fig. 12. Relation between net added cost results of installing fouling detector and plant life time.

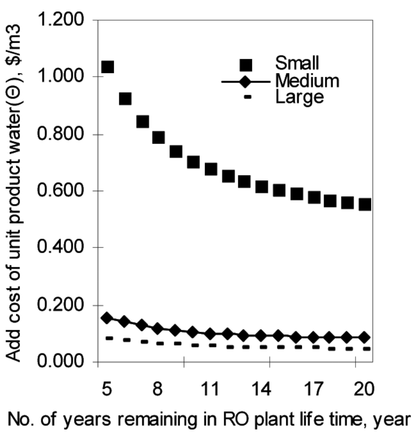

Fig. 13. Effect of plant life time on added cost results of MPC installing.

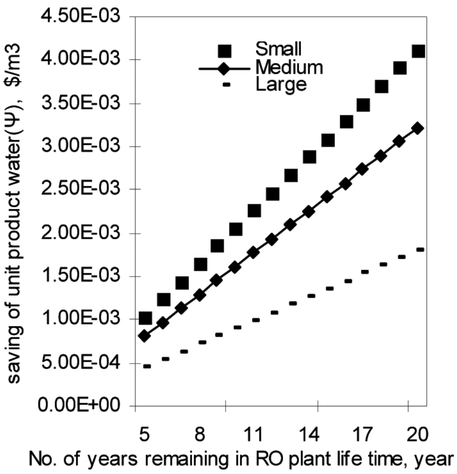

Fig. 14. Relation between MPC saving and plant life.

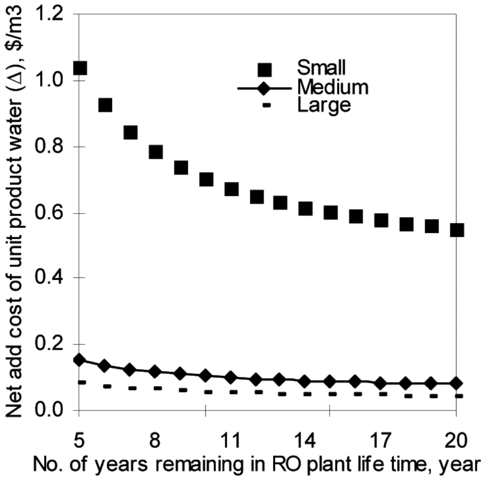

Fig. 15. Effect of MPC net added cost and plant life.

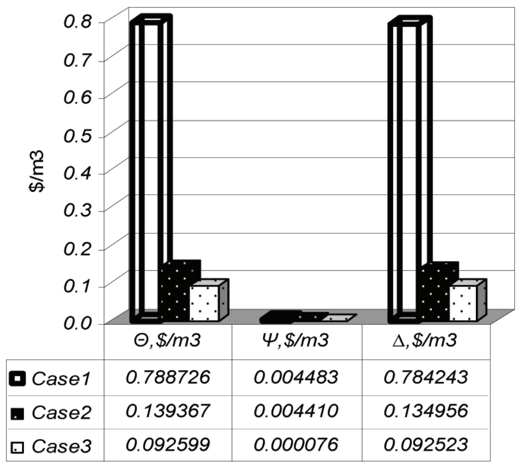

Fig. 16. Economical parameters of case studies.

6. Case studies

Depending on the practical operating data for 3 case studies of SWRO plants with different capacities, the feasibility of operation optimization approach is tested through calculating the economic parameters. Case study plant specifications and economic parameters are given in Tables 2 and 3, respectively.

Case 1 is for a 300 m^3/d (small size) plant located on the west cost of Egypt. It was designed in 2004 to treat seawater of salinity in the range of 33,000 ppm with an acceptable level of control through PLC. Case 2 is for 2100 m^3/d (medium) plant located on the west coast of Egypt. It started to operate in 2007 to treat seawater of salinity in the range of 35,000 ppm with a high level of control system through PLC and SCADA system. Case 3 is for 9000 m^3/d plant (medium scale beach well) located in Fujairah. It represents a major west coast desalination plant in the UAE, operating continuously for more than 4 years.

Referring to operation data for considered case studies given in Table 4, economic parameters estimation is made and results are plotted as shown in Fig. 16 which

Table 2
Case studies specifications, existing control system description

Title			Case 1	Case 2	Case 3
Location			Egypt (Lat.: 31, Long.: 027)	Egypt (Lat.: 31, Long.: 026)	UAE (Lat.: 25, Long.: 055)
Size, m^3/d			300	2,100	9,000
Number of units			2×150 m^3/d	4×300 m^3/d, 6×150 m^3/d	n.a
SWRO unit design	Pres. vess. no.		4	5,3	48
	Membranes	Kind	FILMTEC	FILMTEC	n.a
		Type	8″ SW30-380HR	8″ SW30-380HR	
		No. vessel	3	5,4	6
		Total no.	12	25,12	288
	C_f, ppm		34,000	35,000	39,000
	T_f, °C		25	25	18
	P_f, bar		63	64.2	75
Control system	Description		PLC, digital	PLC + SCADA , digital	PLC, digital, HMI
	Controlled parameters		ORP$_f$, pH$_f$, L&HP$_{HPP}$, pH$_p$, C_p	ORP$_f$, pH$_f$, L&HP$_{HPP}$, pH$_p$, C_p	ORP$_f$, pH$_f$, L&HP$_{HPP}$, pH$_p$ permeate, Reject pressure, C_p, T_f
	Control action		• Parameters limits • An alarm condition indicator • Automatic on/off operation if parameters limit in range	• Automatic sequencing operations • Parameters limits • An alarm condition indicator • Automatic on/off operation if parameters limit in range	

Table 3
Assumed economic parameters used for case studies

Title	Case 1	Case 2	Case 3
Plant daily production (PDP), m^3/d	300	2,100	9,000
Plant availability (PAV)		0.9	
Number of years remaining in plant (n), y	16	20	5
Unit cost of product water (UC), s/m^3	1.6	1.25	0.7
Electric energy supply	380–220 V, ~AC, grid electricity connection		
Specific energy consumption , kWh/m^3	7.3	4.6	4.35
Unit cost of energy,$/kWh	0.06 31	0.0807	0.048
Specific unit cost of energy,$/$m^3$	0.463	0.376	0.21
Energy to product water cost ratio,%	30.87	30.12	30
Membrane replacement cost (5 y life), $/$m^3$	0.082	0.064	0.046
Chemical treatment cost, $/$m^3$	0.058	0.045	0.025
Spares cost	0.080	0.063	0.035
Labor cost	0.066	0.051	0.029

depicts a positive net added cost for the 3 plants which coincides with the general case analysis.

Depending on the same per unit cost used for similar size plants considered in the case studies analysis and general case economical analysis mentioned before, we can estimate a negative net added cost for fouling detector installation.

The main conclusion of the case studies can be summarized in two points. First, installing MPC in SWRO plants with different capacities has no economic applicability. Second, there is a clear expected reduction in desalinated water cost for different RO plant capacities if equipped with advanced fouling detector, which gives it installation priority.

This agrees with the data obtained from the general case economic parameter evaluation mentioned in section 5.2.

The optimization of SWRO operation is an essential issue to decrease the product water cost and the only objection to achieve this target by using MPC is its high cost. Sensitivity analysis was performed for two case studies (Case2 and Case 3) in order to determine the MPC cost value that satisfy economic applicability.
Assuming the plants are provided with MPC from the beginning (i.e., $n = 20$), Fig. 17 presents the values of net added cost corresponding to ±10–50% of the present MPC cost. The figure shows that with 30% reduction in the present MPC cost, case 3 plants seem applicable in the near future.

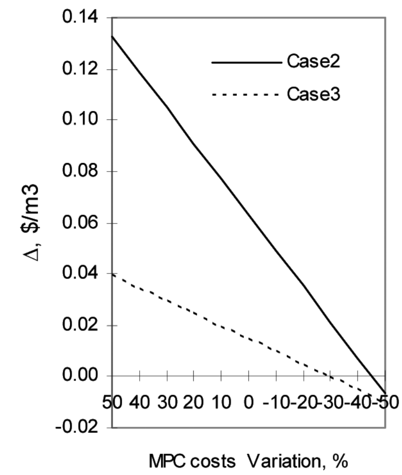

Fig. 17. Case studies (2 and 3) cost sensitivity analysis.

7. Conclusions

- Based on the strategic nature of the product optimization of SWRO plant operations is a critical issue for maintaining low product cost.
- Adoption of installing advanced control systems in RO plants will require effective matching between research establishments and the desalination industry to perform the essential research investigation and test it practically in the field.
- The common exist control system in SWRO is based on the programmable logic controller particularly when provided with (SCADA) system.
- The economic feasibility of advanced controller's installation in SWRO plants depends on the results of an economical analysis to be carried out, operating conditions of those plant and market prices of the controllers must be taken into consideration.
- Depending on the considered economic hypothesis, nowadays there is no expected reduction in the product cost of SWRO plants of all capacities if equipped

Table 4
Comparison between conventional and optimum case studies operational data

Month	T_f, °C	C_f, ppm	Conventional			Optimum		
			P_f, MPa	C_p, ppm	C_w, \$/m^3	P_f, MPa	C_p, ppm	C_w, \$/m^3
Case 1								
January	13	34,000	6.3	91	0.5287	7.40	15	0.399
February	13			91	0.5287	7.40	15	0.399
March	15			107	0.5042	7.23	41	0.4083
April	17			124	0.4796	7.05	71	0.4126
May	20			149	0.4428	6.78	116	0.4099
June	23			174	0.4060	6.51	160	0.3954
July	25			192	0.3814	6.33	189	0.3804
August	25			192	0.3814	6.33	189	0.3804
September	24			183	0.3937	6.42	175	0.3888
October	21			158	0.4305	6.69	130	0.4065
November	18			133	0.4673	6.95	86	0.4130
December	14			99	0.5164	7.32	26	0.4042
Case 2								
January	13	35,000	6.41	92	0.5466	7.544	15	0.41
February	14			100	0.5345	7.454	25	0.416
March	15			108	0.5223	7.364	40	0.420
April	17			125	0.4979	7.184	70	0.425
May	20			150	0.4613	6.914	113	0.424
June	23			175	0.4247	6.644	158	0.414
July	25			191	0.4004	6.449	189	0.398
August	25			191	0.4004	6.449	189	0.398
September	24			183	0.4126	6.554	174	0.405
October	22			166	0.4369	6.734	143	0.417
November	18			133	0.4857	7.094	84	0.426
December	14			99	0.5345	7.454	25	0.416
Case 3								
January	18	39,000	7.5	87	0.485	6.818	80	0.485
February	18			87	0.485	6.818	80	0.485
March	18			87	0.485	6.818	80	0.485
April	18			87	0.485	6.818	80	0.485
May	19			96	0.4765	6.821	88	0.4765
June	19			96	0.4765	6.821	88	0.4765
July	19			96	0.4765	6.821	88	0.4765
August	19			96	0.4765	6.821	88	0.4765
September	20			104	0.4766	6.741	102	0.4767
October	20			104	0.4766	6.741	102	0.4767
November	20			104	0.4766	6.741	102	0.4767
December	20			104	0.4766	6.741	102	0.4767

with model predictive controller. This conclusion depends on the current market prices as well as on the current operating condition. It is important to notice that this conclusion cannot be considered as absolute and can vary in the future.

- Membrane fouling is one of the most important practical problems facing RO plant operators and membrane manufacturers. Early detection of fouling before its negative impacts occur is an effective operation optimization issue.

- Fouling detector provides a techno economic approach to promote the operation optimization of RO systems.

Symbols

a	—	Exponent of Reynolds number
C	—	Salt concentration, kg/m^3
C_B	—	Bulk concentration, kg/m^3
CC	—	Capital cost of optimization equipment, $
C_C	—	Concentrate concentration, kg/m^3
C_f	—	Feed concentration, kg/m^3
C_M	—	Concentration at membrane surface, kg/m^3
C_P	—	Permeate concentration, kg/m^3
$\overline{C}_S$	—	Average concentration
C_w	—	Cost of water, \$/m^3
d	—	Hydraulic diameter, m
D	—	Diffusivity, m^2/s
h	—	Length of membrane, m
i	—	Interest rate
J_S	—	Salt flux, kg/m^2 s
J_V	—	Water flux, m^3/m^2 s
K	—	Mass transfer coefficient
L_P	—	Solution permeability, m^3/m^2 Pa s
L_{Pp}	—	Solution permeability at p, m^3/m^2 Pa s
L_{PT}	—	Solution permeability at T, m^3/m^2 Pa s
m	—	Empirical constant given by Eq.(9)
n	—	Number of years remaining in plant life
OC	—	Operating cost of optimization equipment, \$/y
P	—	Membrane permeability, m/s
P_f	—	Feed pressure, MPa
P_P	—	Membrane permeability at pressure p, m/s
P_T	—	Membrane permeability at T, m/s
R_c	—	SWRO plant recovery ratio
Re	—	Reynolds number
Sc	—	Schmidt number
Sh	—	Sherwood number
T	—	Temperature, °C
T_f	—	Seawater inlet temperature, °C
u	—	Velocity, m/s
UC	—	Unit cost, \$/m^3 water
$\mathrm{UC}_{\mathrm{opt}}$	—	Unit cost at optimum operation, \$/m^3
w	—	Width of membrane, m

Greek

Δ	—	Per unit product net added cost, \$/m^3
δ	—	Density, kg/m^3
η	—	Viscosity, kg/m.s
π	—	Osmotic pressure, Pa
Θ	—	Per unit added cost of water, \$/m^3
σ	—	Membrane reflection coefficient
Ψ	—	Per unit saving of water cost, \$/m^3

Abbreviations

CEM	—	Cost estimation model
HMI	—	Human machine interface
MPC	—	Model predictive controller
PAV	—	Plant availability
PDP	—	Plant daily production, m^3/d
PLC	—	Programmable logic controller
RO	—	Reverse osmosis
%SAV	—	Percentage saving result of using optimization techniques
SCADA	—	System control and data acquisition
SWRO	—	Seawater reverse osmosis

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