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Cost analysis in RO desalination plants production lines: mathematical model and simulation

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ABSTRACT

In this article, the cost analysis of a m^3 of desalinated water by reverse osmosis (RO) has been extensively studied. Although the capacities of production lines in these plants are normally different, a desalination plant is usually constituted by a set of production lines with identical capacities, which correspond to the total production capacity. Optimization cost of a more efficient production line affects the economy of scale. We report a mathematical model based on expressions related to costs based on production capacity. This study aims to present and analyze costs simulation for the production line in seawater desalination plants by RO technology. The work scope corresponds to production capacities of small desalination plants in the range between 500 and 15,000 m^3/d in the Canary Islands. This range of options is the most widely deployed in this region. The methodology involves the collection and processing of statistical data, applied to research studies related to the thesis. Based on this, we plotted all the costs data in bar diagram and box and whisker diagrams. The outliers values study was carried out as well as the Kolmogorov–Smirnov and Shapiro–Wilk tests were carried out based on the Hubera's M, Tukey's biweight, Hampel's M and Andrews' wave estimators. Afterwards, the factorial analysis was carried out using the Barlett and Kaiser–Meyer–Olkin tests; the possible mathematical models were analyzed. This study provides an innovative aspect in costs analysis due to the fact that the study focused exclusively on the search for more technologically efficient production line with lower cost impact to the plant. The equation presented corresponds to the mathematical model based on the statistical data adjusted by 98% of the real cost for small desalination plants within the range mentioned. The existing deviations for each production range would be outlined from the analysis of the simulation regarding the mathematical equation of the calculated costs. To conclude, this article presents as a final result and conclusions, the mathematical model obtained, the corresponding real simulation graphic getting among other data, the existing deviation between the values obtained in this study and what is shown on the real data based on the seawater desalination costs, noting that it is less than 1.5%, both for the

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most efficient production line and for the remaining lines observed within the range previously established in the particular case of the Canary Islands.

Keywords: Reverse osmosis; Unit costs; Canary Islands; Desalination; Operating parameters

1. Introduction

Canary Islands are pioneers in desalination process in Spain. In fact, the first seawater desalination plant in Canary Islands and Spain was installed in Lanzarote in 1964.

It was precisely, in this decade, thanks to the development of technology, great steps were taken to obtain a never known boom. The reverse osmosis (RO) technology has been greatly developed during this time. Particularly, in Canary Islands, which have served as a model for the rest of the Spanish territory, more than 95% of the desalinated water uses the RO process (see Fig. 1).

2. Reverse osmosis desalinated water m^3 cost analysis

In this section, all events happened during the last years in relationship with the RO water desalination and the impact on the m^3 cost due to the installation design factors were discussed.

In 2001, Andreas Poullikkas concludes an article estimating a worldwide cost of 0.44 €/m^3 [1].

In 2002, the magazine "Agricultura" presents an article by María Amparo Melián Navarro and José María Cámara Zapata about the desalination techniques and costs, stating that during 2001 the cost of RO desalinated seawater was around 0.42 and 0.84 €/m^3 [2], when costs studies are finally presented through a Doctoral Thesis presented by Mr. David Martinez Vicente. In his thesis, he studies the costs of desalination with RO in big plants, from 10.000 to 140.000 m^3/day of desalinated water production, considering an energy consumption of 4.4 kWh/m^3 and a cost of 4 c€/kW. The author, based on data of different desalination plants in Spain and on his own investigation, proved that total costs for plants producing 10.000 m^3/day around 0.5576 and 0.6276 €/m^3 depending on the source of water, that is from well or direct source [3].

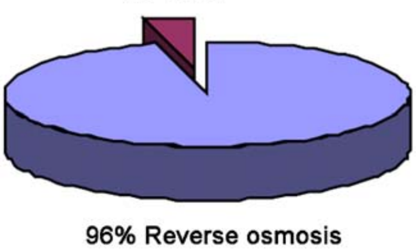

Fig. 1. Desalinated seawater production in Canary Islands, October 2010 [10].

For the plants with productions of 140.000 m^3/day of desalinated waters, the values fluctuate between 0.4095 and 0.4678 €/m^3 depending on the source of water (from well or direct source).

In 2004, during the water management and planning, Iberian congress comments about the cost of desalinated water in Spain near 0.53 €/m^3 [4].

In 2005, the magazine Desalination publishes an article by Wilf, and Bartels in which it is shown that the boosting pumps efficiency has to be around the 88%, the Pelton turbines and interchangers should be around 94% and electrical engines near the 96% [5].

In 2008, the magazine Desalination publishes an article by Akili et al. about the advances in new technologies in seawater desalination. More specifically, they comment the improvement in the membranes production technologies and the introduction of energy recovery systems. For them, the cost of seawater desalination by RO is around 0.53 €/m^3 [6].

In 2009, the magazine Desalination publishes an article by Catherine Charcosset based on a revision of the desalination process membranes using renewable energy. In his article, it is commented that the RO requires, in particular, between 3 and 10 kWh/m^3 of electrical energy for drinking water production and that the conversion factor fluctuates between 25 and 45% [7].

In the last two years, 2010 and 2011, the realized studies show a cost of 0.4 €/m^3 for big desalinating plants.

In 2012, the magazine, desalination and water treatment, published an article in which it shows the total costs for seawater desalination by RO, being able to see all the same. It shows the costs in the range from 1.64 €/m^3 to 500 m^3/day plant and 0.64 €/m^3 to 15,000 m^3/day plant [8].

It is important to state that in the Canary Islands the tendency for building up small-sized desalinating plants is due to the fact of the existence of many gullies in the landscape, spreading many small population areas quite far from each other.

<table>
<tr><td colspan="4">STUDY RESULTS OF THE THESIS</td></tr>
<tr><td colspan="4">GRAPHING COSTS</td></tr>
<tr><td>bar diagram</td><td colspan="2">dispersion diagram</td><td>box and whisker diagram</td></tr>
<tr><td colspan="4">STUDY outliers (control charts)</td></tr>
<tr><td colspan="4">FINAL DATA INTERPRETATION</td></tr>
<tr><td colspan="2">Kolmogorov-Smirnov test</td><td colspan="2">Shapiro-Wilk test</td></tr>
<tr><td colspan="4">factorial analysis</td></tr>
<tr><td colspan="2">Bartlett test</td><td colspan="2">Kaiser-Meyer-Olkin (KMO) test</td></tr>
<tr><td colspan="4">REALIZATION OF MATHEMATICAL MODELS</td></tr>
<tr><td colspan="2">univariate model</td><td colspan="2">model based on weighted least squares</td></tr>
</table>

Fig. 2. Methodological process diagram.

Conducted a comprehensive review of the past and the above, we present our work, which studied the costs are: energy, amortization, reagent consumption, replacement cartridge filters, membrane replacement, personal, and environmental maintenance.

3. Methodology applied for the mathematical modeling

To conclude the investigation of this doctoral thesis, we study the obtained results so that we can find the mathematical model which will define our investigation. We represent graphically all data. Therefore, we have used the program SPSS, version 20, [9], which is a software tool to represent statistical functions. For each cost, we represent the results in a bar diagram, dispersion diagram, and box and whisker diagram, obtaining some data that are important for the study and for possible elimination of certain values.

In order to study possible values that can be anomalous for our model, in addition to the information obtained earlier, we make control graphics for each cost to be sure of the values we are going to retire of the study.

As discussed in the aforementioned sections, we kept three most representative costs (amortization, staff, and energetic) with a production of 5,000–15,000 m^3/day.

As said costs, previously defined as Fundamentals, we make the Kolmogórov–Smirnov, Shapiro–Wilk tests based on estimations of M de Hubera, biponderate of Tukey, M de Hampel y onda de Andrews observing that the contrast distribution keeps normal during the whole process, as well as the total cost. We proceeded afterwards to make the factorial analysis with the Barlett y de Kaiser–Meyer–Olkin tests.

On the basis of these, we analyze the possible mathematical models using the program SPSS, version 20, and we have analyzed the possible models, in our investigation, stating that the cost is a unique variable which depends on the other eight independent variables.

So our mathematical model can answer a univariate model or a model based on weighted least squares. The following Fig. 2 shows the methodological process.

4. Results

4.1. Results for the univariate model

Initially, we present the model description, as the dependent variable total costs, and other costs are part of the covariates (see Table 1).

In Table 2, the tests of between-subjects effects are shown and it represents a number of basic results for the model calculation.

Presented in Table 3 are the parameters obtained in this first model, responding to a confidence interval of 95%.

Introducing the term end result that defines us the mathematical model.

$$\begin{aligned} F\ (\text{univariate}) = {} & 10.613 + 0.317A + 0.715R + 20.886F \\ & + 0.674M + 0.962P + 0.890MO \\ & + 1.427MA + 0.825E \end{aligned}$$

where the coefficients (*A*, *R*, *F*, *M*, *P*, *MO*, *MA*, and *E*) correspond to the values of the amortization costs, reagent consumption, replacement cartridge filters, membrane replacement, staff, maintenance, environmental, and energy consumption.

Table 1
Grand average

Dependent variable: total			
Mean	Error	Confidence interval 95%	
		Lower limit	Upper limit
87.623[a]	.029	87.554	87.691

[a] Covariates appearing in the model are evaluated at the following values: amortization = 10.8944, reagents = 2.9419, filters = 0.2188, membranes = 1.0081, staff = 21.0150, maintenance = 3.4063, environmental = 4.3913, energetic = 43.7469.

Table 2
Tests of between-subjects effects

Dependent variable: total

Origin	Sum of squares	gl	Mean square	*F*	Sig.	Partial eta squared	Parameter noncentrality	Observed power[b]
Corrected model	17.491744	8	2.186468	161.571620	.000	1.000	1.292572963	1.000
Intersection	.003	1	.003	.245	.636	.034	.245	.072
Amortization	.009	1	.009	.642	.449	.084	.642	.107
Reagents	.001	1	.001	.096	.766	.013	.096	.058
Filters	.027	1	.027	2.004	.200	.223	2.004	.232
Membranes	.016	1	.016	1.174	.314	.144	1.174	.156
Staff	9.482	1	9.482	700.717	.000	.990	700.717	1.000
Maintenance	.088	1	.088	6.535	.038	.483	6.535	.595
Environmental	.097	1	.097	7.161	.032	.506	7.161	.634
Energetic	.071	1	.071	5.248	.056	.428	5.248	.506
Error	.095	7	.014					
Total	140.335079	16						
Total corrected	17.491838	15						

Table 3
Model parameters

Dependent variable: total

Parameter	*B*	Error típ.	*t*	Sig.	Confidence interval 95%		Partial eta squared	Parameter noncentrality	Observed power
					Lower limit	Upper limit			
Intersection	10.613	21.442	.495	.636	−40.091	61.316	.034	.495	.072
Amortization	.317	.395	.801	.449	−.618	1.252	.084	.801	.107
Reagents	.715	1.971	−.309	.766	−5.271	4.051	.013	.309	.058
Filters	20.886	14.754	1.416	.200	−14.001	55.773	.223	1.416	.232
Membranes	.674	.622	1.084	.314	−.797	2.146	.144	1.084	.156
Staff	.962	.036	26.471	.000	.876	1.048	.990	26.471	1.000
Maintenance	.890	.866	2.556	.038	.166	4.263	.483	2.556	.595
Environmental	1.427	.533	2.676	.032	.166	2.688	.506	2.676	.634
Energetic	.825	.360	2.291	.056	−.027	1.676	.428	2.291	.506

4.2. Results model based on weighted-least-squares

In a second case, the model of weighted least squares, choosing ponderadora variable energy consumption as one of the variables with more weight in the total cost (see Table 4). The data ANOVA are presented in Table 5.

As in the previous model, we present in Table 6 the coefficients belonging to the new model.

Introducing the term end result that defines us the mathematical model.

$$\begin{aligned} F\ (\text{leastsquares}) = {} & 10{,}383 + 0.326A + 0.018R + 21.059F \\ & + 0.033M + 0.963P + 2.214MO \\ & + 1.416MA + 0.806E \end{aligned}$$

4.3. Results of the simulation with real data (case of 5,000 m^3/day)

Once we have studied the mathematical models, we will make a comparison with the actual data. We are going to study the production line of

Table 4
Model description

Dependent variable		Total
Independent variable	1	Amortization
	2	Reagents
	3	Filters
	4	Membranes
	5	Staff
	6	Maintenance
	7	Environmental
	8	Energetic
Weighting	Origin	Energetic
	Power value	−2.000

Table 5
Data ANOVA

	Sum of squares	*gl*	Mean square	*F*	Sig.
Regression	36.978415998	8	4.622302000	187.247291	.000
Residual	172.799	7	24.686		
Total	36.978588797	15			

Table 6
Model parameter

	Unstandardized coefficients		Standardized coefficients		*t*	Sig.
	B	Error tip.	Beta	Error tip.		
Parameter	10.383	20.967			.495	.636
Amortization	.326	.388	.018	.021	.842	.428
Reagents	.018	1.947	−.002	.008	−.318	.760
Filters	21.059	14.648	.006	.004	1.438	.194
Membranes	.033	.587	.003	.003	1.140	.292
Staff	.963	.035	.726	.027	27.377	.000
Maintenance	2.214	.853	.040	.015	2.594	.036
Environmental	1.416	.518	.176	.064	2.736	.029
Energetic	.806	.352	.039	.017	2.350	.051

5,000 m^3/day, which according to [8], is the most efficient production line within the range studied. We obtained five results of the total costs of desalination plants in operation in May, studying and normal deviations and comparing the results of the mathematical model chosen.

We present the results (Table 7) obtained with the actual data being observed that are fully adequate to our research, which leads us to confirm that the mathematical model responds weighted least square with reality.

These values that we present in Figs. 3 and 4 shows the normal value and the normal deviation.

We now present the calculation of the adjustment or error about reality. We will take the values for the upper and lower limits, so we figured the worst cases.

$$\begin{aligned} \text{Adjustment} &= ((71.45 - 70.92)/71.45) \times 100 \\ &= 0.74\% \\ \text{Adjustment} &= ((71.45 - 73.37)/71.45) \times 100 \\ &= 1.28\% \end{aligned} \tag{1}$$

Table 7
Descriptive

Production			Statistical	Error típ.
Cost 5,00000	Average		71.6520	.26079
	Confidence interval 95%	Lower limit	70.9279	
		Upper limit	72.3761	
	Median cropped 5%		71.6450	
	Median		71.6000	
	Variance		.340	
	Desv. típ.		.58316	
	Mínimum		70.98	
	Máximum		72.45	
	Rank		1.47	
	Amplitude interquartile		1.10	
	Asymmetry		.367	.913
	Kurtosis		−1.005	2.000

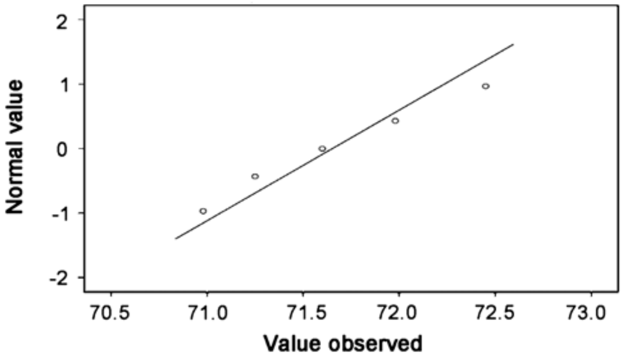

Fig. 3. Figure *Q–Q* normal cost for the production of 5,000 m^3/d.

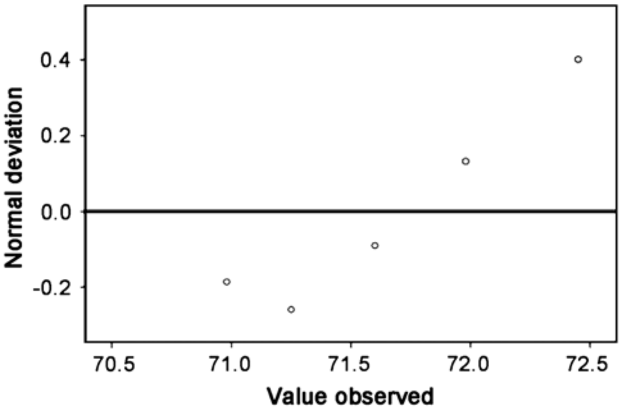

Fig. 4. Figure *Q*–*Q* normal without cost trend for the production of 5,000 m^3/d.

5. Conclusions

(1) Our mathematical model can answer a univariate model or a weighted least squares model, based on the total cost, based on eight independent variables that match the eight different cost types and most common has a desalination plant seawater RO.

(2) The model of weighted least squares is the best suited and provides better results than the univariate model. Data were used according to [8].

(3) The results of the standard deviation values of 0.58316 and the standard deviation of 0.4 that gives the actual simulation model indicate that the weighted least squares is appropriate.

(4) The adjustment or margin of error presents the mathematical model chosen is higher than 98.5% compared with the reality in the worst case.

References

[1] A. Poullikkas, Optimization algorithm for reverse osmosis desalination economics, Desalination 133 (2001) 75–81.
[2] J.M. Cámara, M.A. Melián, Las técnicas de desalación y sus costes, Agricultura (2002).
[3] D. Martínez Vicente, Estudio de la viabilidad técnico-económica de la desalación de agua de mar por ósmosis inversa, Tesis Doctoral. Universidad de Murcia, 2002.
[4] M. Latorre, Costes económicos y medioambientales de la desalinización de agua de mar, IV Congreso Ibérico de Gestión y Planificación del Agua, 2004.
[5] M. Wilf, C. Bartels, Optimization of seawater RO systems design, Desalination 173 (2005) 1–12.
[6] Akili D. Khawaji, Ibrahim K. Kutubkhanah, Jong-Mihn Wie, Advances in seawater desalination technologies, Desalination 221 (2008) 47–69.
[7] Catherine Charcosset, A review of membrane processes and renewable energies for desalination, Desalination 245 (2009) 214–231.
[8] F.E.O. José. J. Jaime Sadhwani, L. Alvarez, More efficient production line with desalination plants using reverse osmosis, Desalination and Water Treatment (August 2012).
[9] Software SPSS, versión 20.
[10] M. Hernández Suárez, Datos estadísticos sobre el agua en Canarias. Centro Canario del Agua, 2007.