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Article

Multi-criteria optimization for seawater desalination

Optimización multicriterio para desalar agua de mar

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Abstract

In this study, the decision-making process for seawater desalination and its possible use in industry are addressed. Six desalination technologies were considered: multistage instantaneous distillation, multiple effect distillation, vapor compression distillation, reverse osmosis, electrodialysis, and nanofiltration. The problem was analyzed from several perspectives, including the evaluation of environmental, technical, and economic criteria, which were broken down into eight sub-criteria. The alternatives were evaluated considering three different multi-criteria decision-making (MCDM) methodologies: AHP, ELECTRE, and TOPSIS. The results show that the best option for desalinating seawater is reverse osmosis, followed by nanofiltration, thermal desalination methods, and lastly, electrodialysis. The results for the different methods showed the same ranking and no major discrepancies. It is concluded that desalination using membranes is a good option that could be used to supply water for various purposes, such as in industry.

Keywords: Multiple-criteria decision making, MCDM, AHP, ELECTRE, TOPSIS, seawater desalination.

Resumen

Este estudio trata la toma de decisiones para la desalación de agua de mar y su posible uso en la industria. Considera la evaluación de seis tecnologías de desalación, como destilación instantánea de múltiple etapa, destilación múltiple efecto, destilación por compresión de vapor, ósmosis inversa, electrodiálisis y nanofiltración. Toma en cuenta criterios ambientales, técnicos y económicos, y desglosados en ocho subcriterios. Se usan los métodos de optimización multicriterio (MCDM): AHP, ELECTRE y TOPSIS. Se determinó que la mejor alternativa para desalar agua de mar es la ósmosis inversa, seguida por la nanofiltración, luego los métodos térmicos de desalación y, en último lugar, la electrodiálisis. Los resultados mostraron el mismo *ranking* sin mayores discrepancias. Se concluye que la desalación mediante membranas es una buena opción para abastecer de agua para diversos usos públicos, por ejemplo a pequeños agricultores, en zonas donde existe escasez de este recurso.

Palabas clave: toma de decisiones multicriterio, MCDM, AHP, ELECTRE, TOPSIS, desalación de agua de mar.

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Introduction

The recent issues associated with climate change affect the natural water regeneration cycle. Water is an increasingly scarce resource, with approximately 20% of the world's population living in areas without sufficient water, and another 10% approaching this situation. Of all the fresh water in the world, 69% is found at the poles and on the highest mountain peaks, in a solid state. Another 30% resides in soil moisture or in deep aquifers. Only 1% of the world's fresh water drains through hydrographic basins in the form of streams or rivers and is deposited in lakes, lagoons, and other surface bodies of water, and it can also end up in aquifers (Fritzmann, Löwenberg, Wintgens, & Melin, 2007). Therefore, the search for options for sustainable water supplies is required. The desalination of seawater is an important alternative to this problem.

The methods used to desalt water have advantages and disadvantages, which depend on various factors associated with each process. Studies have focused on generating cost databases (operating and capital) for different desalination methods (Ettouney, El-Dessouky, Faibish, & Gowin, 2002). In addition, the costs of desalinating seawater and brackish water are different because of the TDS (total dissolved solids), which include minerals, salts, metals, cations, and anions dissolved in water. More saline water (higher TDS) portends higher desalination operating costs (Karagiannis & Soldatos, 2008; Zotalis, Dialynas, Nikolaos, & Angelakis, 2014). Some studies have correlated data and generated mathematical models on costs and capital for desalination methods (Wittholz, O'Neill, Colby, & Lewis, 2008).

Regarding the environmental factors involved in desalination, there are complexities in the pre- and post-treatments of membrane processes (Fritzmann *et al*., 2007). Thermal processes, on the other hand, do not require delicate treatment (Gude, 2015). Finally, the costs associated with water transportation to and from the desalination plant should be considered (Zhou, 2005).

In terms of MCDM techniques, authors have compared the effectiveness of AHP and PROMETHEE for the best energy supply option (Georgiou, Mohammed, & Rozakis, 2015). The comparison considers supply alternatives and environmental, economic, social, and technical criteria.

In terms of research, one of the first studies using MCDM evaluated the desalination of brackish water in Jordan (Mohsen & Al-Jayyousi, 1999) by employing alternative technologies such as the multiple distillation effect (MED), multiple stage instantaneous distillation (MSF), reverse osmosis (RO), electrodialysis (ED), steam compression distillation (CV), and the AHP method. Other studies addressed the selection of the best seawater desalination plant using AHP (Hajeeh & AI-Othman, 2005) and considering MED, MSF, CV, and RO technologies and alternative plant construction. Research has also been undertaken on the use of diffuse AHP with three desalination alternatives (MED, MSR, and RO) to supply fresh water to the state of Kuwait (Hajeeh, 2006). Another study integrated two stages and utilized diffuse AHP and TOPSIS for the desalination of brackish water (Ghassemi & Danesh, 2013) and for obtaining drinking water using electrodialysis. Studies have been conducted using MCDM tools for sustainable cities (Si, Marjanovic-Halburd, Nasiri, & Bell, 2016) and solar energy for desalination (Shatat, Worall, & Riffat, 2013).

Regardless of the various works employing MCDM technology, to our knowledge there are no available studies on the desalination of seawater for its possible use in public consumption and agroindustry in developing countries. Therefore, this work evaluates the desalination of seawater with the following multi-criteria tools and technological alternatives: MSF, MED, CV, ED, RO, and NF.

Methodology

In this section, the basic characteristics of the desalination and MCDM methods used in the present study are mentioned.

Methods for desalting

- *Multiple stage flash distillation* (*MSF*). By abruptly reducing the pressure of seawater below its equilibrium vapor pressure, sudden evaporation occurs. The maximum recovery ranges between 12-20%.
- *Multiple effect distillation* (*MED*). MED uses the same principle as the MSF process but differs in its evaporation process. Seawater is sprayed on the surface of the tubes of an evaporator, forming a thin film that favors rapid boiling and evaporation. The maximum recovery ranges between 30-40%.
- *Distillation with vapor compression* (*CV*). The heat necessary for boiling seawater is obtained from the steam removed from an evaporator and reinjected in the first stage after being compressed, to raise its saturation temperature. The maximum recovery ranges between 40-50%.
- *Reverse osmosis* (*RO*). The RO method is used to extract dissolved solids from water, such as salts, using a semipermeable membrane with high permeability for water but very low permeability for salts. It does not involve a water phase change. Water passes through the driven membrane by a pump, which raises its pressure to a higher value than its natural osmotic pressure. High pressure pumps are used with pressures ranging from 5.4 to 8.2 MPa. The fraction of desalted water ranges between 30-45%.
- *Nanofiltration* (*NF*). NF is a membrane filtration that works in a fashion similar to reverse osmosis. The difference is that the membrane is not as closed and has lower feed pressure. In addition, it does not eliminate monovalent ions from water. The trans-membrane pressures vary from 1.5 to 5 MPa.
- *Electrodialysis* (*ED*). ED is a electrochemical separation method using charged membranes and a difference in electric potential to separate ionic and other compounds, and is frequently used to desalinate brackish water.

The following are the main characteristics of the MCDM used:

- Analytic Hierarchy Process (AHP). Proposed by Thomas L. Saaty (Saaty, 1980), this is a classic decision-making process. It is applied in almost all areas and can be summarized by the following stages:

- Model the problem as hierarchies containing the decision objectives, the alternatives for achieving it, and the criteria and sub-criteria for evaluating the alternatives.
- Establish priorities among the elements in the hierarchy, making judgments based on pairwise comparisons of the elements; definition and weighting of the decision variables.
- Synthesize judgments to generate an ideal hierarchical set of priorities for evaluating the different alternatives to the solution of the decision problem.
- Check the consistency of judgments between the evaluation criteria and available alternatives.
- Obtain a final decision according to the results of the process.

Elimination and Choice Expressing REality (Et Choix Traduisant la Realité, ELECTRE): To select an alternative from among several alternatives, compare each one based on specific evaluation criteria (Benayoun, Roy, & Sussman, 1966). For each criterion, a weight or relative weight, *w,* is established. The relative advantages and disadvantages are evaluated among the alternatives in each criterion and ranked in order of preference from best to worst.

This method uses the ranking relation $A_hS_jA_k$, which indicates that alternative (or scenario) A_h is preferable to A_k in the criterion (or attribute), considering that the ranking of A_h is greater than or equal to that of A_k. That is, A_h is considered as good or better than A_k. The method establishes two conditions to prove that A_h is preferable to A_k, or outranks it: the outranking relation and two tables or matrices (concordance and discordance), normalized to the values of the qualifications, and with m alternatives and n selection criteria. It requires a normalized decision matrix of the scores. The elements in this matrix are a_{ij}, that is, the evaluation of each alternative A_i in criteria j.

Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS): This technique uses the concept of an ideal alternative, based on the absolute notion of ideal (Zeleny & Starr, 1977), which is the alternative that is closest to the ideal. It considers the subtleties of the ideal and builds an operational method. Developed by Hwang and Yoon in 1981, it is based on the fact that a given alternative is at the shortest distance from an ideal alternative that represents the best (positive ideal or simply ideal) and at the greatest distance from an alternative that represents the worst (ideal negative or anti-ideal).

Results

The parameters shown in Table 1a are the criteria (C_j) and their environmental, economic, and technical sub-criteria (SC_j). The technological alternatives are shown in Table 1b. Desalination is analyzed by means of AHP, ELECTRE, and TOPSIS. The results of each method are mentioned below.

Application of AHP

A comparison matrix of the sub-criteria was generated. The weights of each criterion were normalized and obtained, with the average of the elements in the corresponding sub-criterion row (Table 1c). For each sub-criterion, a matrix was generated with the alternatives and their respective scores, in pairs. This resulted in a matrix of priority vectors with technologies and sub-criteria, and the priority vector of the sub-criterion (Table 1d).

Table 1. Application of AHP.

Table 1a. Criteria and sub-criteria of AHP.

Criteria	**Sub-criterion**	**Definition**
Environmental (C1)	Waste management (SC1)	Handling and elimination of brine
Technical (C2)	Operational complexity (SC2)	Skills in operating technology
	Pretreatment and adaptability (SC3)	Technology/water fed
	Reliability and stability (SC4)	Technology in stationary conditions
	Water recovery (SC5)	Water generated/water fed
	Quality of treated water (SC6)	Quality of generated water (ppm of salts)
Economic (C3)	Fixed capital cost (SC7)	Investment in equipment, facilities, and construction
	Operating costs (SC8)	Expenses: salaries, supplies (energy), products, services, and maintenance

Table 1b. Alternative technologies.

Alternative	Technology
A1	MSF
A2	MED
A3	CV
A4	RO
A5	ED
A6	NF

Table 1c. Standardized sub-criteria comparison matrix and sub-criteria priority vector.

	SC1	SC2	SC3	SC4	SC5	SC6	SC7	SC8	*w*
SC1	0.06	0.12	0.09	0.17	0.02	0.02	0.06	0.08	0.08
SC2	0.02	0.04	0.02	0.08	0.02	0.02	0.05	0.07	0.04
SC3	0.03	0.08	0.05	0.13	0.02	0.02	0.05	0.06	0.05
SC4	0.02	0.02	0.02	0.04	0.02	0.02	0.06	0.08	0.03
SC5	0.12	0.12	0.09	0.08	0.05	0.02	0.04	0.05	0.07
SC6	0.19	0.16	0.18	0.13	0.19	0.07	0.05	0.06	0.12
SC7	0.25	0.20	0.23	0.17	0.29	0.35	0.23	0.20	0.23
SC8	0.31	0.24	0.32	0.21	0.38	0.49	0.47	0.40	0.35

Table 1d. Matrix of priority vectors between technologies and sub-criteria and sub-criteria priority vector.

Technology	SC1	SC2	SC3	SC4	SC5	SC6	SC7	SC8
MSF	0.293	0.028	0.298	0.081	0.027	0.294	0.071	0.057
MED	0.171	0.051	0.231	0.038	0.101	0.165	0.067	0.145
CV	0.314	0.100	0.231	0.038	0.163	0.294	0.037	0.068
RO	0.095	0.348	0.059	0.324	0.420	0.117	0.466	0.303
ED	0.046	0.175	0.059	0.192	0.058	0.029	0.098	0.068

NF	0.078	0.29 5	0.12 0	0.32 4	0.22 7	0.09 8	0.25 9	0.35 5
Priority vector, *w*	0.078	0.03 9	0.05 3	0.03 4	0.07 2	0.12 8	0.23 9	0.35 3

At the end, each technology value (specific sub-criterion) was multiplied by the corresponding priority vector associated with the sub-criterion, and by each sub-criterion. The values were added to obtain the use score for each technology. The technologies were ranked according to their convenience of use (Table 1e).

Table 1e. Priority vectors for each technology and their rankings.

Technology	***Score***	***Ranking***
MSF	0.1202	5
MED	0.1253	3
CV	0.1251	4
RO	0.3004	1
ED	0.0763	6
NF	0.2526	2

Application of ELECTRE

The concordance matrix (Table 2a) is shown with the weight proportions when technology A_h is as good or better than technology A_k, according to Table 1d. In the cells, the weights corresponding to the sub-criteria are added. Subsequently, the discordance matrix is generated (Table 2b), and the largest difference between the sub-criteria when technology A_h is worse than technology A_k is explicitly shown in the cells. (If technology A_h is always greater or equal, it is identified with a "zero.")

Finally, the preference threshold, *p,* is 0.5351, and the indifference threshold, *q,* is 0.5401. Table 2c shows the comparison of the technologies by rows and then by columns, using concordance pairs and discordance matrices. Technology A_h dominates A_k if C (*h*, *k*) is greater than or equal to the preference or outranking threshold, and only if D (*h*, *k*) is less than or equal to the indifference threshold or is not outranked. For example, the MSF technology dominates the MED technology, is outranked by the CV technology, with a difference equal to zero, and takes a third place ranking along with MED and CV.

Table 2. Use of ELECTRE.

Table 2a. Concordance Matrix for desalination technologies.

	MSF	**MED**	**CV**	**RO**	**ED**	**NF**
MSF	0	0.5351	0.3285	0.2603	0.2603	0.2603
MED	0.4648	0	0.5932	0.2603	0.6857	0.2603
CV	0.5434	0.3181	0	0.2603	0.3324	0.2603
RO	0.7396	0.7396	0.7396	0	0.9463	0.5580
ED	0.7396	0.3142	0.6675	0	0	0
NF	0.7396	0.7396	0.7396	0.4070	1	0

Table 2b. Discordance Matrix for desalination technologies.

	MSF	**MED**	**CV**	**RO**	**ED**	**NF**
MSF	0	0.2947	0.3462	1	0.4603	1
MED	0.4872	0	0.5320	1	0.5401	1
CV	0.2796	0.2593	0	1	0.5401	1
RO	1	0.7203	0.8147	0	0	0.2542
ED	1	0.7203	1	0.9203	0	0.9630
NF	0.8037	0.4661	0.8813	0.4903	0	0

Table 2c. ELECTRE results.

Technology	**Dominance per row**	**Dominance per Column**	**Difference of dominances**	**Ranking**
MSF	MED	CV	0	3rd
MED	CV - ED	MSF - NF	0	3rd
CV	MSF	MED	0	3rd
RO	ED - NF	-	2	1st
ED	-	MED - RO - NF	-3	4th
NF	MED - ED	RO	1	2nd

Application of TOPSIS

The relative weights of the sub-criteria and the decision matrix were the same as with AHP (Table 3a. Weighted normalized matrix).

Table 3. Application of TOPSIS.

Table 3a. Weighted normalized decision matrix.

	SC1	SC2	SC3	SC4	SC5	SC6	SC7	SC8
MSF	0.0231	0.0011	0.0159	0.0028	0.0019	0.0377	0.0170	0.0204
MED	0.0135	0.0020	0.0124	0.0013	0.0073	0.0211	0.0160	0.0514
CV	0.0247	0.0039	0.0124	0.0013	0.0117	0.0377	0.0090	0.0241
RO	0.0075	0.0137	0.0032	0.0113	0.0303	0.0150	0.1119	0.1074
ED	0.0036	0.0069	0.0032	0.0067	0.0042	0.0037	0.0235	0.0243
NF	0.0061	0.0116	0.0064	0.0113	0.0164	0.0126	0.0623	0.1257

The ideal positive solution and the ideal negative solution were then calculated, which corresponded to the maximum and minimum values associated with each column, respectively. For example, the ideal positive solution in sub-criterion 1 is 0.0247, which is the maximum value in that column. On the other hand, the ideal negative solution associated with that column is 0.0036. The results are provided in Table 3b. The distances were calculated, which represent the geometric distances to the values of the ideal positive and negative solutions (see Table 3c). Finally, we obtained the relative proximities to the ideal solution based on the scores associated with each of the options, in order to rank the evaluated technologies and determine which one to implement. The closer the value of a technology is to 1, the better the option. The results are shown in Table 3d.

Table 3b. Positive and negative ideal solutions.

	SC1	SC2	SC3	SC4	SC5	SC6	SC7	SC8
A+	0.0247	0.0137	0.0159	0.0113	0.0303	0.0376	0.1119	0.1257
A-	0.0036	0.0011	0.0031	0.0013	0.0019	0.0037	0.0090	0.0204

Table 3c. Matrix of positive and negative distances.

	d+	d-
MSF	0.1453	0.0412
MED	0.1260	0.0391
CV	0.1464	0.0424
RO	0.0362	0.1391
ED	0.1435	0.0171
NF	0.0610	0.1201

Table 3d. Relative proximity and ranking.

Technology	R	Ranking
MSF	0.2240	5
MED	0.2367	3
CV	0.2246	4
RO	0.7935	1
ED	0.1067	6
NF	0.6632	2

Table 1d shows that the most important sub-criteria were SC8 (operating costs, with 35% of importance), SC7 (fixed capital cost, with a weight of approximately 24%), and SC6 (water quality, with an approximate weight of 12.8%). SC7 and SC8 comprised the economic criterion, and together they constituted more than half of the total importance, with the sum of their weights close to 60%. That is, the economic criterion is the most important in the decision making. Table 4 presents the weights from the pairwise evaluation using the AHP method and those used for the decision-making process with the ELECTRE and TOPSIS methods.

Table 4. Weights of the criteria and sub-criteria.

Criteria	Weight (%)	Sub-criteria	Weight (%)
Environmental (C1)	7.87	Waste management (SC1)	7.87
Technical (C2)	32.81	Operational complexity (SC2)	3.94

		Pre-treatment and adaptability (SC3)	5.37
		Reliability or stability (SC4)	3.49
		Water recovery (SC5)	7.21
		Quality of treated water (SC6)	12.80
Economic (C3)	59.33	Fixed capital costs (SC7)	23.99
		Operating costs (SC8)	35.33

Although the technical criterion had more sub-criteria, that does not mean that those criteria were more important than the others. Several sub-criteria corresponding to the technical criterion were analyzed, but none was of a critical nature to influence the final decision. In fact, while sub-criteria such as the cost of fixed capital (investment cost of the plant) were more important, the most significant was the operating cost associated with the process, since it varied greatly depending on the selected process, and it highly influences its feasibility.

Table 5. Scores and rankings of the different desalination technologies.

Technology	Score			Ranking		
	AHP	*ELECTRE*	*TOPSIS*	*AHP*	*ELECTRE*	*TOPSIS*
MSF	0.1202	0	0.2240	5	3	5
MED	0.1253	0	0.2367	3	3	3
CV	0.1251	0	0.2246	4	3	4
RO	0.3004	2	0.7934	1	1	1
ED	0.0763	-3	0.1066	6	4	6
NF	0.2526	1	0.6631	2	2	2

Discussion

When comparing the technologies, ED had the lowest ranking and was in last place. Although it is one of the best alternatives for desalinating brackish water, its performance for desalinating seawater is lower due to the high concentration of salts. It has low energy consumption when treating waters with salt contents lower than 3 500 ppm of TDS, but seawater can have up to 30 000 ppm.

The thermal technologies then follow: MSF came in fifth place, CV was in fourth place, and finally, MED was in third place. These have some advantages over membrane methods but are not more important, according to the evaluation. They are characterized as providing slightly warmer water with lower salt concentrations than OR or NF. In addition, they emit chemical compounds into the environment (anti-fouling), which generates harmful long-term effects in the discharge area (Gude, 2015). The last advantages in sub-criterion 3 refer to the quality or purity of the fresh water obtained from those processes. Thermal technologies have an advantage of desalting water and leaving it with minimum concentrations of salts (TDS less than 50 ppm). These are appropriate technologies to obtain water with minimum saline content, although some regulations allow up to 1 500 ppm of TDS. They have higher energy consumption than other options, which makes the process more expensive, especially in developing countries where fuels are expensive or inaccessible, such as in the Middle East.

Lastly, RO is in first place, and NF is in second place. RO performs better in preventing the selective passage of ions and salts through the membrane, generating water with lower TDS concentrations, which is a positive outcome. To achieve that, however, a higher pressure gradient is required, that is, a higher energy consumption. Recent studies consider it possible to desalinate water using NF, obtaining a quality similar to that obtained by RO but with a lower energy consumption (Adham, Cheng, Vuong, & Wattier, 2003). Despite that result, reverse osmosis in sub-criterion 8 has a greater weight than most of the other sub-criteria because it is a one-stage process, unlike NF which employs two stages. NF is a more complex process to operate and control in comparison with RO. In addition, the water recovery capacity and the quality of the salt concentration of the final water are exceeded. Therefore, RO is the most viable option for desalinating seawater for possible agro-industrial purposes, and even domestic consumption.

Finally, the hierarchy or ranking is the same for AHP and TOPSIS. In ELECTRE, a slight difference is noted, and the three thermal processes are in third place (MED, MSF and CV). ELECTRE presents a more imprecise algorithm than TOPSIS and AHP, which use ranking to produce scores. The ELECTRE method only produces a hierarchy. The scores consist of the differences in the dominances between the rows and columns. It is observed that both TOPSIS and AHP, along with the MSF, MED, and CV technologies, present very similar scores. It can be said that among the methods, the ELECTRE method yields less precise results and is more complex to operate.

As for AHP and TOPSIS, both methods use the same decision matrix and the same ranking. They reflect very good results and have high coherence among them.

Conclusions

The use of MCDM delivered results that are currently consistent with reality, and membrane desalination processes are used and developed mainly by RO. The advantages of NF are recent and are expected to improve over time.

All the MCDM methods used resulted in similar rankings. The best option for the hierarchical order of the methods (AHP, ELECTRE, and TOPSIS) is RO, NF, MED, CV, MSF, and ED.

The results are highly dependent on economic criteria because energy consumption is relevant and directly related to the operating costs of the processes.

The results are concordant with reality. For example, in Latin American countries, membranes show a clear superiority over thermal methods for the desalination of seawater, due to the costs associated with each of the processes.

In the future, a similar study would use renewable and applied energies in specific agricultural sectors located near sources of seawater.

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