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Optimal Selection of Desalination Systems using Fuzzy AHP and Grey Relational Analysis

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Water scarcity is an alarming global problem for a growing population with depleting sources of fresh water. Desalination is thus becoming an important solution for water management to address such looming shortage of the municipal water supply. At present, several technologies dominate the desalination industry which can be categorized either as a thermal process such as multi-stage flash distillation or a membrane process such as that of reverse osmosis. New desalination systems are also being developed to make the process more cost-effective and energy efficient. Hence, this work proposes a systematic approach for optimal selection of desalination systems using fuzzy analytic hierarchy process (FAHP) and grey relational analysis (GRA). Fuzzy AHP addresses the vagueness involve in the trade-off of the criteria or attributes used in evaluating the alternatives. On the other hand, the GRA solves the multiple criteria decision problem by aggregating the entire range of performance attribute values for every alternative into a single score in spite of incomplete information. An illustrative case study was presented wherein five desalination systems namely reverse osmosis (RO), combined reverse osmosis and forward osmosis (RO-FO), electrodialysis (ED), multi-stage flash distillation (MSF), and combined forward osmosis and membrane distillation (FO-MD) were evaluated. These desalination systems were compared to each other with respect to energy requirement, land footprint, system efficiency, economic viability, and maturity of technology. Sensitivity analysis was also done to determine the robustness of the modeling results from the variation of weights of the criteria.

1. Introduction

In year 2040, it is projected that 33 countries will experience high water stress according to the report by World Resources Institute (WRI) released in August 2015. The water stress, which is the measure of water availability, is affected by various factors including climate change, economic development, urbanization, and population growth. The rapid increase in population has led to excessive exploitation of available freshwater resources (Ghalavand et al., 2015). Thus, a need to explore other possible alternatives to compensate the shortage in drinking water availability is critically needed, and seawater is seen to be the best option, which comprises 97% of the Earth's water. Utilization of seawater could lessen the water stress, especially in coastal areas where the source of water is commonly brackish. Desalination is the most widely used technology in converting salty water into potable water. There are various desalination techniques that are commercially available which could be used in utilizing seawater. Such techniques include thermal method, ion exchange and membrane–based technologies. However, selection on what type of desalination technology to be used for a given location or for a specific purpose is still difficult to identify. Several parameters should be considered in effectively identifying the optimal desalination system such as environmental considerations, technical aspect and economical viability. These parameters could be efficiently evaluated using various tools on multi-criteria decision making (MCDM).

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Analytic hierarchy process (AHP) is a widely used MCDM tool originally developed by Saaty (1977) to derive ratio-scale priorities from pairwise comparison matrices. AHP evaluates various alternatives based from a given number of criteria, which is expressed in a hierarchical structure (Ghassemi and Danesh, 2013). One disadvantage attributed in using AHP is that some data gathered from subjective and personal judgment of decision makers are considered arbitrary or vague (Chian-Son, 2002). Thus, the fuzzy AHP was developed to address the vagueness associated with the conventional AHP. The latest study related to desalination with the application of MCDM is reported by Ghassemi et al. (2013). A hybrid fuzzy AHP and TOPSIS was used for the selection of the optimum desalination technology among six commercially available desalination alternatives. However, in recent years, researchers are gaining interest in hybridization of desalination technologies, which are not yet commercially available. Thus, the need to incorporate hybrid desalination systems to the list of alternatives should be further investigated.

This study aims to identify the optimal desalination system using a hybrid technique from two multi-criteria decision making tools namely the calibrated fuzzy AHP and grey relational analysis (GRA). The calibrated fuzzy AHP was used to derive the trade-off weights whereas GRA was used to measure the desirability of an alternative through its closeness or similarity with the reference sequence, i.e., the idealized attributes of the best alternative. Tripathy and Tripathy (2016) reported that GRA could be used in the selection process of the best alternative; however, it should be conducted in an optimal parameter setting to obtain the required output utilizing minimum resources. In this study, two hybrid desalination systems, RO-FO and FO-MD, were added in the list of alternatives to evaluate the performance of the hybrid system. Three other alternatives include reverse osmosis (RO), multi-stage flash distillation (MSF) and electrodialysis (ED). For an illustrative case study, these alternatives were assessed using five criteria: energy requirement, land footprint, system efficiency, economic viability and maturity of technology.

2. Methodology

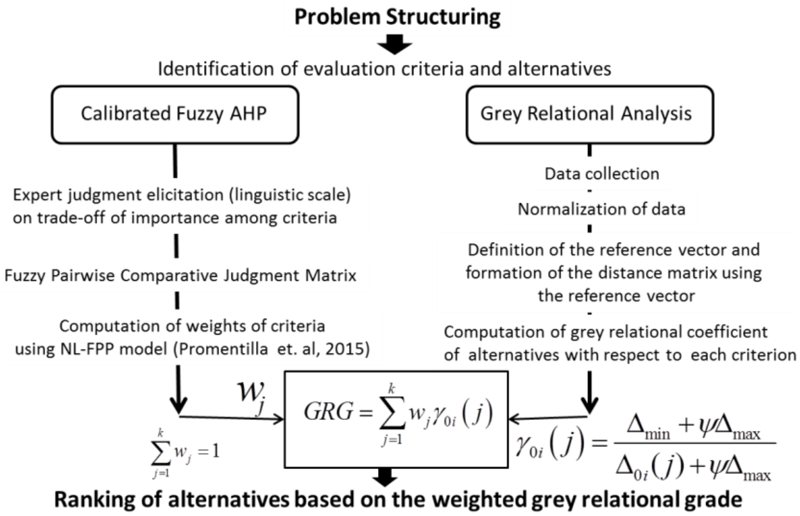

Figure 1: A methodological framework in the selection of desalination systems.

The proposed framework for the optimal selection of desalination systems is described in Figure 1. First, the problem is structured in a hierarchy fashion such that the uppermost level is the goal, followed by the set of the multi-level evaluation criteria and the generation of alternatives in the lowermost level. Value judgments are then elicited from experts to derive the importance weights of the criteria using the calibrated Fuzzy AHP (Promentilla et al, 2016). The verbal judgments for pairwise comparison are represented by triangular fuzzy numbers (TFN) instead of Saaty's fundamental 9-point scale (Saaty, 1977). The membership function of these fuzzy numbers is calibrated through real pairwise comparisons of measurable properties such as that of area of geometrical figures (Ishizaka and Nguyen, 2013). For example, in the recent study of Promentilla et al. (2016), when an *object i* is perceived as moderately larger than *object j*, the verbal judgment can be approximated by a TFN < 1.5, 2, 3.2 >. The triples <1.5, 2, 3.2> represent the lower bound, modal value, and upper bound of the TFN for the vague term "moderately more". Note that the degree of fuzziness is observe to be greater to verbal judgments such as "strongly more, <1.5, 3, 5.6>" and "very strongly more, <3.0, 5, 7.9>". On the other hand, the "absolutely or extremely more" is calibrated by TFN <6.0, 8, 9.5>. After the pairwise comparison matrix is filled up with these fuzzy numbers, ratio-scale weights of the *n* objects were computed using the nonlinear fuzzy preference programming approach described in Promentilla et.al. (2015). Note that these weights can be computed for at least (*n-1*) pairwise comparative judgments. The global weights of the criteria are then use for the computation of the weighted grey relational grade (GRG).

The GRG is obtained from the grey relational analysis which is originally proposed by Deng (1989) to measure the magnitude of correlation between reference series and comparison series. Details of this procedure for MCDA can be found, for example, in Kuo et al (2008). The GRG is typically described as a generalized distance function. Thus, the higher the value of GRG of an alternative, the closer it is to the reference or idealized alternative. Note that the collected data need to be normalized as performance scores may have different units resulting to a dataset with values ranging between 0 and 1 inclusive wherein 1 denotes the idealized score (best performance). The resulting matrix (with size of ***n x k***) is composed of comparison series ($x^*_i(j)$), i.e., row vectors of ***n*** compared alternatives containing normalized data of ***k*** performance scores. On the other hand, the reference series ($x_0(j)$) is denoted by row vector of 1s. This reference series is used to generate the distance matrix which is the difference or distance ($\Delta_{0i}(j)$) between the reference value and each comparison value. In this distance matrix, the minimum differerence (Δmin) and maximum difference (Δmax) was used to compute the grey relational coefficient as shown by the following equation:

$$\gamma_{0i}\left(j\right)=\frac{\Delta_{\min}+\psi\Delta_{\max}}{\Delta_{0i}(j)+\psi\Delta_{\max}} \quad (1)$$

Note that the distinguishing coefficient (ψ) with a typical value of 0.50 is just used expand or compress the range of grey relational coefficient. The GRG of each alternative is then computed (see Figure 1) as the weighted sum of the grey relational coefficients for all the criteria.

3. Case Study: selection of optimal desalination system

There are two main categories for desalination: thermal method and membrane-based method. Ghalavand at al. (2015) reported that the multi-stage flash distillation, subcategory of thermal method, is considered as the main desalination process accounting to 60% of the total world production capacity. In terms of membrane-based method, the two major processes are reverse osmosis and electrodialysis as stated by Husain et al. (1997). These three desalination processes were selected as alternatives to be evaluated using MCDM approach. In addition to these, two hybrid desalination systems were added in the list of alternatives, RO-FO and FO-MD. Incorporation of FO to the conventional RO process was assumed to compensate the high energy requirement of the RO system (Bamaga et al., 2011), in which FO system can be used for energy recovery (Eusebio et.al., 2016). For the hybridization of forward osmosis and membrane distillation, it was reported that FO-MD system is becoming an attractive alternative and a promising desalination technology due to the high efficiency of MD in the recovery process of draw solution, which utilizes low grade heat (Zhao et al., 2014). As illustrated in Figure 2, five desalination system alternatives are evaluated based from five criteria: energy requirement, land footprint, system efficiency, economic viability and maturity of technology.

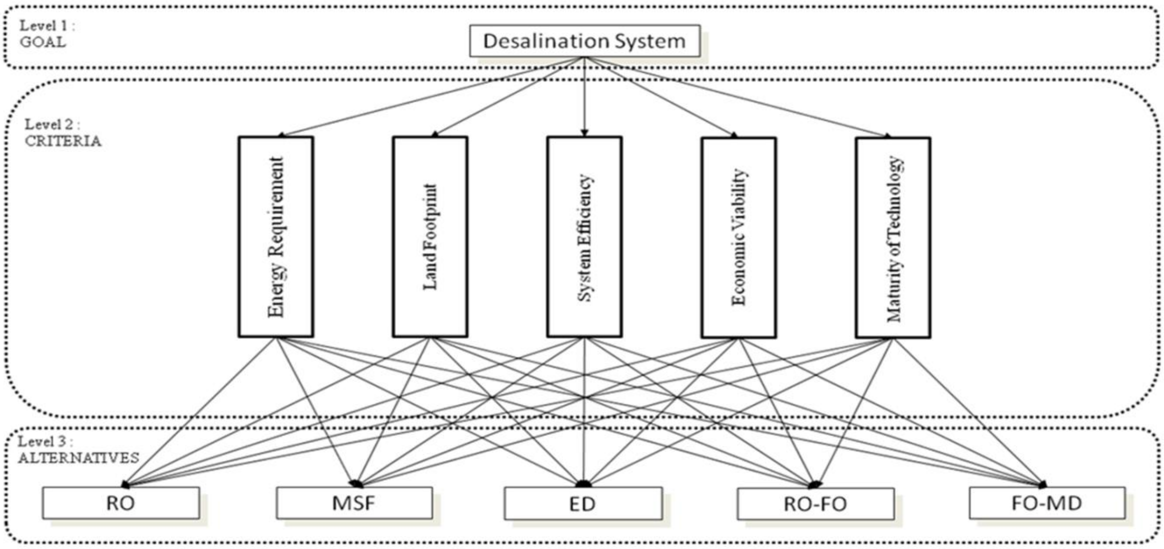

Figure 2: The decision hierarchy for the optimal selection of desalination systems.

Table 1: Sample fuzzy pairwise comparative judgement matrix

	Energy Requirement	Land Footprint	System Efficiency	Economic Viability	Maturity of Technology
Energy Requirement	$\langle 1,1,1 \rangle$	$\langle 3,5,7.9 \rangle$	$\langle 0.31,0.5,0.83 \rangle$	$\langle 1,1,1 \rangle$	$\langle 1.5,3,5.6 \rangle$
Land Footprint		$\langle 1,1,1 \rangle$	$\langle 0.11,0.13,0.17 \rangle$	$\langle 0.13,0.2,0.33 \rangle$	$\langle 0.31,0.5,0.83 \rangle$
System Efficiency			$\langle 1,1,1 \rangle$	$\langle 1.2,2,3.2 \rangle$	$\langle 3,5,7.9 \rangle$
Economic Viability				$\langle 1,1,1 \rangle$	$\langle 1.5,3,5.6 \rangle$
Maturity of Technology					$\langle 1,1,1 \rangle$

Table 2:Desalination system evaluation criteria and scoring system

Criteria	Score				
	1	2	3	4	5
Energy Requirement	Very Low Energy	Low Energy	Medium Energy	High Energy	Very High Energy
Land Footprint	Very Small	Small	Medium	Large	Very Large
System Efficiency	Low Salt Rejection	Low-Moderate Salt Rejection	Moderate Salt Rejection	Moderate-High Salt Rejection	High Salt Rejection
Economic Viability	Very Low Cost	Low Cost	Moderate Cost	High Cost	Very high Cost
Maturity of Technology	Research Stage	Development Stage	System Modification and Improvement	Well Established System	Commonly used for Industrial Application

Calibrated Fuzzy AHP was used to quantify the relative importance of each criterion with respect to the goal. Pairwise comparative judgment matrix was populated with the value judgement from the domain expert as shown in Table 1. Using the NLP model (Promentilla et al., 2015), priority vector was calculated with a fuzzy consistency index of 0.74. The corresponding importance weight of the five criteria are 0.2279 for energy requirement, 0.0489 for the land footprint, 0.4079 for the system efficiency, 0.2279 for economic viability and 0.0875 for the maturity of technology. This result shows that the most important criterion is the system efficiency, which is evidently seen from the recent studies of most researchers, wherein they are trying to improve the performance (Mehta et al., 2014) and optimize the operating condition of the desalination system (Liu et al, 2014). GRA was utilized in evaluating the performance of each alternative based from the five criteria. A scoring system was created to categorize the desirability of an alternative with respect to each criterion as defined in Table 2.

Table 3: Decision matrix for desalination system alternatives and estimation of grey relational grade with ranking (Ψ = 0.50)

Alternatives	Energy* Requirement	Land Footprint	System* Efficiency	Economic* Viability	Maturity of Technology	Grey Relational Grade	Ranking
RO	3	2	3	3	5	0.4676	5
MSF	3	4	4	3	3	0.5182	3
ED	5	2	4	2	3	0.5616	2
RO-FO	1	3	3	4	2	0.4934	4
FO-MD	2	3	5	4	2	0.7805	1

*Mehta et al., 2014

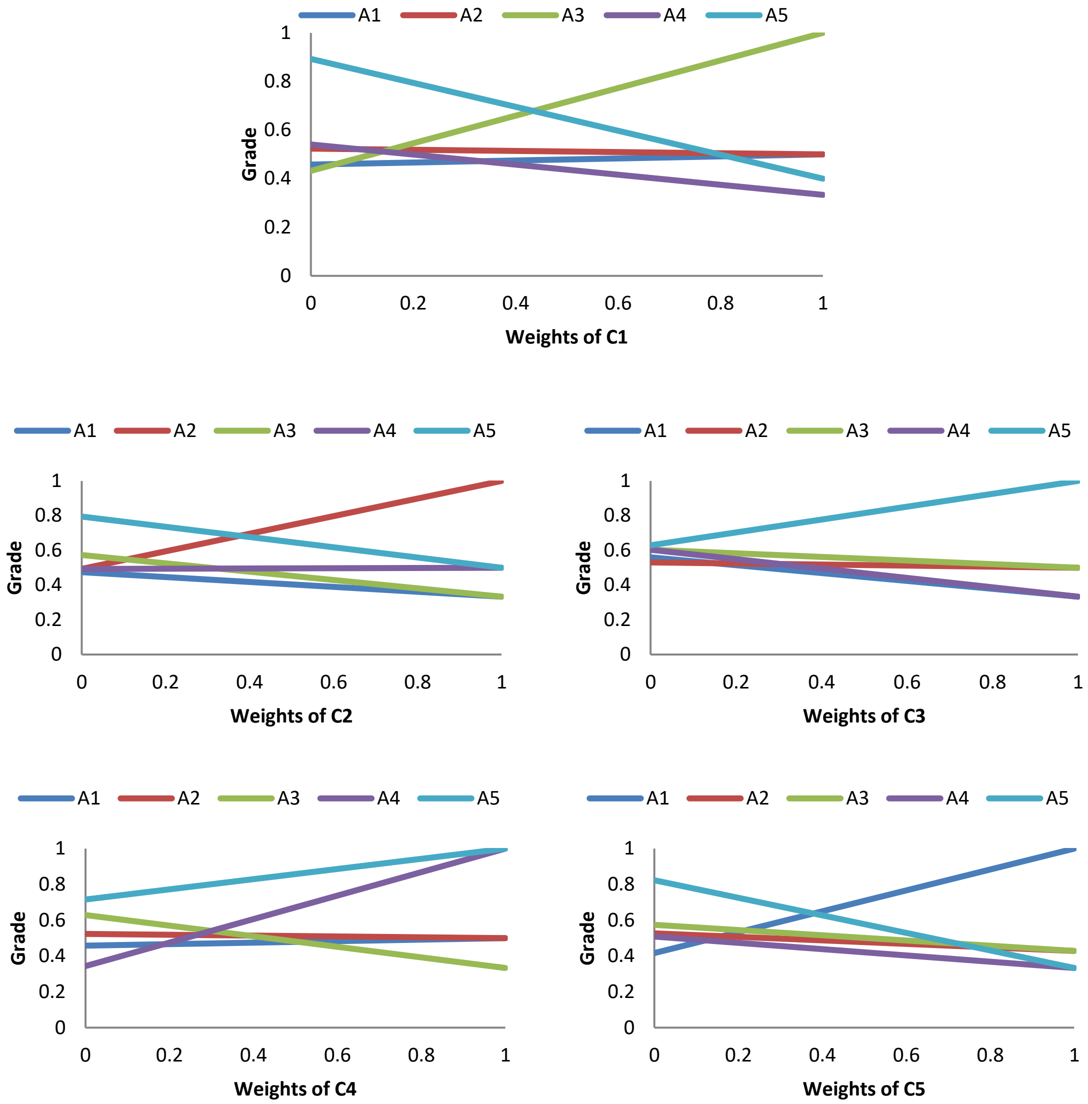

Figure 3: Sensitivity analysis of the priority weights of the five alternatives for the optimal selection of desalination systems at various criteria weight intervals (0 to 1): (C1) energy requirement, (C1) land footprint, (C3) system efficiency, (C4) economic viability, (C5) maturity of technology

The output response of the expert domain was tabulated in Table 3 with the calculated grey relational grade (GRG) that represents the overall performance of each alternative at distinguishing coefficient (Ψ) of 0.50. It was observed that FO-MD system obtained the highest value of GRG with the value of 0.7805. According to Triphathy and Tripathy (2016), the higher GRG value leads to the optimum combination of input parameters. The ranking shows that the most preferred desalination system is the hybrid FO-MD system, while the RO system attained the lowest ranking. This result was found to be coherent with the findings obtained by Zhao et al. (2014) with FO-MD system as more preferred as compared to stand alone RO system.

Sensitivity analysis was performed to determine the effect of varying the criteria weights in the selection of the optimal desalination system. To investigate the effect of changing the weight of each criterion to the ranking of alternatives, the priority weight of each criterion was varied from 0 to 1 with an interval value of 0.1 while the preference ratio of the remaining criteria to each other are kept constant. This process was also done to the other four criteria as shown in Figure 3. It should be noted that the most important criterion based on the computed priority vector is the system efficiency (C3). Thus, as observed in Figure 3-C3, changing the weight of C3 from 0 to 1 has no effect on the ranking of FO-MD (light blue line), which is always the most preferred alternative. The same trend was observed in varying the weight of economic viability (C4). For the system efficiency (C1), increasing the weight to more than 0.5 will change the preferred alternative to electrodialysis. While for land footprint and maturity of technology, increasing the weights to more than 0.4 will change the preferred alternative to MSF and RO, respectively.

4. Conclusions

Selection of the optimal desalination system was conducted using the calibrated fuzzy AHP-GRA method. Five desalination alternatives (RO, MSF, ED, RO-FO, FO-MD) were evaluated based from five criteria (energy requirement, land footprint, system efficiency, economic viability and maturity of technology). System efficiency was found to be the most significant criterion obtaining the highest importance weight of 0.4079. FO-MD system was observed to be the most preferred desalination technology among other alternatives from the evaluation performed through GRA method. For further studies, it is recommended to incorporate the degree of confidence of the value judgement from the domain expert.

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