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Desalination membrane selection using group fuzzy analytical hierarchy process

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ABSTRACT

This paper presents a group fuzzy analytical hierarchy process (FAHP) model for the selection of water desalination membranes. In addition to literature, experts from the pharmaceutical industry sector and academia were involved in setting and evaluating the criteria to be used in the selection process. Technical criteria focus on parameters concerning the type and configuration of the material of membrane, operational parameters concerning the work conditions under which the membrane will function and efficiency parameters concerning permeability, salt rejection and environmental performance over the lifecycle of the membrane. Non-technical criteria focus on the supply chain finance, volume and time parameters. The fuzzy opinions of 12 experts were aggregated using the aggregation of individual judgment (AIJ) method to obtain the weights of seven technical and five non-technical criteria and their corresponding sub-criteria using Chang's FAHP method. Obtained weights are then used to select the best reverse osmosis (RO) desalination membrane alternative among three different alternative membrane types widely used in the pharmaceutical industry; ESPA1 which is characterized by its energy saving among RO membranes during the filtration processes and produces around 2,100 gallons of permeate flow each day, CPA2 which is known for its high salt rejection and produces around 2,250 gallons of permeate flow each day, and LFC3 which is known for its low fouling and produces around 2,100 gallons of permeate flow each day. Experts agreed that technical criteria are far more important than non-technical criteria. Results show that salt rejection efficiency is the most important technical criteria, the cost is the highest-ranked non-technical criteria and CPA2 is the most preferred alternative.

Keywords: Decision making; Desalination; Fuzzy analytical hierarchy process; Membrane; Multi criteria

1. Introduction

Membranes are selective barriers used between two adjacent solutions that allow the passage of a certain ingredient and retains others [1]. Worldwide, it is estimated that 56% of desalination water is produced from membrane processes [2]. In water purification processes, membranes are used to separate dissolved solids, salts and other chemical components to obtain pure water. In the pharmaceutical industry, membranes are used to produce injectable drug solutions to ensure a sterile, consistent and safe product within standard preparation procedures.

Membrane technology is a promising solution for the treatment of oily sewage due to its advantages such as cost-effectiveness, chemical additives, standard installation and operation at room temperature compared to traditional methods [3]. In the general term, membrane filtration comprises the physical separation of undesirable impurities from substance solutions through a semi-permeable membrane. Depending on membrane technical principles, osmotic pressure is necessary to operate this technique. Membrane

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processes such as microfiltration (MF), nanofiltration (NF), ultrafiltration (UF) and reverse osmosis (RO) are currently used for water reuse, brackish water and seawater [4]. MF is a pressure-driven process where separated compounds are 0.1–0.2 μm such as nanoparticles. UF membrane process can separate compounds between 0.005 ≈ 10 μm. NF is capable of removing ions that contribute significantly to the osmotic pressure hence allows operation pressures that are lower than those RO while RO is a pressure-driven technique used to remove dissolved solids and smaller particles; RO is only permeable to water molecules. Selecting among the many types of membranes is a multi-criteria decision making (MCDM) process that accounts for the technical properties of each membrane in addition to economic and environmental factors.

MCDM is the process of finding the best alternative among a set of feasible alternatives by comparing the performance of each alternative on desired technical and non-technical criteria to maximize desired benefits. Analytical hierarchy process (AHP) is a structured mathematical tool used to solve MCDM problems and requires certainty in evaluating the relative importance of each decision criteria against other criteria using numerals to better estimate the weights of all criteria [5]. Fuzzy concept enhances the traditional AHP method to capture the fuzziness of decision-makers' opinion by fuzzy linguistic terms such as "More important", "Important", "Less important" and "Unimportant". The fuzzy set allows intermediate values between AHP finite numbers [6]. The fuzzy analytical hierarchy process (FAHP) is a hierarchy structure where fuzzy memberships are used to estimate the relative comparisons [7]. Chang [8] introduced an extent analysis method for the synthetic values of the pair-wise comparisons. The author handled FAHP sets using triangular fuzzy (TF) numbers for pair-wise comparisons.

Several researchers used AHP, Fuzzy and FAHP in solving MCDM problems in applications from the various industries. Srdjevic et al. [9] used AHP to select among four possible water treatment methods used in colored manufacturing. Selection criteria included the energy required, costs, effectiveness and ease of application. Moreover, the authors considered environmental impact and skill needs for workers to apply the process. Tan et al. [10] proposed a fuzzy AHP model for quantitative and qualitative MCDM in process engineering selection problems based on aggregated judgments of experts. The authors presented three case studies to illustrate their technique where an expert's degree of confidence is reflected in pairwise comparisons. Ren et al. [11] presented a fuzzy model for the sustainability assessment of biomass-based technologies for hydrogen production. Multiple decision-makers were engaged in fuzzy MCDM evaluation of qualitative and imprecise fifteen criteria including environmental, social-political, economic and technological aspects. Sadr et al. [12] developed a fuzzy model to select an appropriate membrane treatment technology for potable and non-potable reuse water scenarios. Technical, socio-cultural and economic criteria were considered to rank ten different membrane technologies. The study revealed that water quality and community acceptance were the main criteria in nano-filtration and RO scenarios where the maximum level of treatment is expected. Other studies used FAHP to better decide among alternatives. In 1997, Weck found a method to evaluate various production cycle alternatives by adding the mathematics of fuzzy logic to the classical AHP [13]. Dalalah et al. [7] and Kilincci and Onal [14] developed FAHP models with quantitative and qualitative factors for selecting the best supplier among a set of alternatives. Anojkumar et al. [15] used FAHP to choose a suitable pipe material in the sugar industry among five stainless steel grades. Selection criteria included yield strength, hardness, corrosion rate, and cost. Manekar et al. [16] used FAHP to assess the performance of eight pretreatment modules for membrane separation processes in the textile cluster to achieve the zero effluent discharge.

This study identifies important technical and nontechnical criteria used in selecting among RO desalination membranes used in the pharmaceutical industry. The study investigates the combined effect of several experts in evaluating criteria in a FAHP model.

2. Chang FAHP model

FAHP involves the task of finding scores (i.e., priority vector) to a set of alternatives via an uncertain pair-wise comparison of the criteria to the alternatives. In this model, triangular membership functions are used to model the pair-wise judgments of the experts, and any subsequent operations will be expressed in fuzzy operations consequently. Chang FAHP method is characterized by its simplicity and structured steps for TF numbers; contrary to the many methods presented in the literature, the computational requirements in this method are relatively low. The defuzzification is used to switch the fuzzy results into crisp and comprehendible AHP values. However, this method allows only for TF numbers to be used [8].

2.1. Fuzzy sets and fuzzy numbers

Within a universe set X, there is a fuzzy number A of X that is defined by a membership function $\mu_A(x)$ which maps each element x in X to a real number within (0–1) interval. A fuzzy number A of a triangle membership function is denoted by $A = (l, m, u)$, where $0 < l \leq m \leq u < \infty$. Fig. 1 shows a typical TF number; l is the smallest possible value, m is the most promising value and u is the largest possible value. The triplet numbers (l, m, u) can be used to describe a fuzzy evaluation on X with the following membership function:

$$\mu_A(x) = \begin{cases} \dfrac{x-1}{m-1} & l \leq x \leq m \\ \dfrac{u-x}{u-m} & m \leq x \leq u \\ 0 & \text{otherwise} \end{cases} \tag{1}$$

As all the subsequent operations upon the pair-wise comparison are held in a fuzzy environment, the following operations will be used throughout the presentation of the model. For any two fuzzy numbers, say A_1 and A_2, the addition, multiplication, division, and reciprocals can be

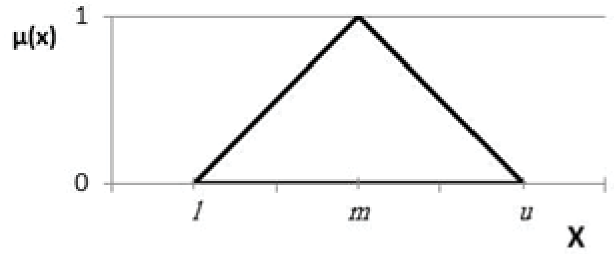

Fig. 1. Triangular fuzzy numbers

found as follows: Let $A_1 = (l_1, m_1, u_1)$ and $A_2 = (l_2, m_2, u_2)$; $l_i, m_i, u_i > 0$ for all i. The addition of the two fuzzy numbers is given by

$$A_1 + A_2 = \left(l_1 + l_2, m_1 + m_2, u_1 + u_2\right) \quad (2)$$

The multiplication operator can be performed as:

$$A_1 \times A_2 = \left(l_1 l_2, m_1 m_2, u_1 u_2\right) \quad (3)$$

The division can be found by:

$$\frac{A_1}{A_2} = \left(\frac{l_1}{l_2}, \frac{m_1}{m_2}, \frac{u_1}{u_2}\right) \quad (4)$$

The reciprocal of fuzzy number A_i is:

$$A_i^{-1} = \left(\frac{1}{u_i}, \frac{1}{m_i}, \frac{1}{l_i}\right) \quad (5)$$

For this study, the expert pair-wise evaluation process has been restricted to the six evaluation levels proposed by Büyüközkan et al. [13]. The linguistic variables are mapped to fuzzy scales as shown in Table 1.

2.2. Aggregation of individual judgment

Aggregation of individual judgment (AIJ) method which is described by the following: Let K be the number of decision-makers who are evaluating the alternatives. Thus, we have K evaluation matrices, where $Ak = \{a_{ijk}\}$ $\forall i = 1,..,n$, $j = 1,\ldots,n$, $k = 1,\ldots,k$. Note that $a_{ijk} = \{l_{ijk}, m_{ijk}, u_{ijk}\}$ represents the relative importance of element i to j assessed by expert k, [16].

The representing fuzzy numbers out of the K evaluations are given by:

$$l_{\mathrm{ij}} = \min_{k=1,2,\ldots,K} l_{\mathrm{ijk}}, m_{\mathrm{ij}} = \sqrt[K]{\Pi_{k=1}^{K} m_{\mathrm{ijk}}}, u_{\mathrm{ij}} = \max_{k=1,2,\ldots,K} u_{\mathrm{ijk}} \quad (6)$$

To validate data, the consistency ratio (CR) of the above matrix has to be computed. CR should be less than or equal 10% for the evaluations to be consistent and hence, acceptable. Otherwise, evaluation should be carefully revised by the experts to provide consistent evaluations and hence, reliable solutions to the set goal. The consistent ratio can be computed by the following equations:

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}(n)} \quad (7)$$

$$\mathrm{CI} = \frac{\left(\lambda_{\max} - n\right)}{\left(n-1\right)} \quad (8)$$

where CI is the consistency index which shows the strength of the evaluation response and RI (n) is the random consistency Index calculated by random response simulation which is reported by Saaty [18] for various decision matrix dimensions. The random index has a specific value for every matrix size as shown in Table 2 where n is the size of the square matrix. The parameter $\lambda_{\max}$ is the largest Eigenvalue of the comparison matrix which can be easily calculated using MATLAB software [19].

Table 2
Random consistency index [17]

n	RI (n)
1	0.00
2	0.00
3	0.58
4	0.9
5	1.12
6	1.24
7	1.32
8	1.41
9	1.45
10	1.49

Table 1
Triangular fuzzy (TF) scales for criteria judgment (Kahraman scale)

Linguistic scale	TF scale	Reciprocal linguistic scale	TF reciprocal scale
Just equal (JE)	(1, 1, 1)	Just equal (JE)	(1, 1, 1)
Equally important (EI)	(1/2, 1, 3/2)	Equally important (EI)	(2/3, 1, 2)
Weakly more important (WMI)	(1, 3/2, 2)	Weakly less important (WLI)	(1/2, 2/3, 1)
Strongly more important (SMI)	(3/2, 2, 5/2)	Strongly less important (SLI)	(2/5,1/2, 2/3)
Very strongly more important (VSMI)	(2, 5/2, 3)	Very strongly less important (VSLI)	(1/3, 2/5, 1/2)
Absolutely more important (AMI)	(5/2, 3, 7/2)	Absolutely less important (ALI)	(2/7, 1/3, 2/5)

In FAHP, the fuzzy comparison matrices which encompass triangular fuzzy numbers (TFN's) should be converted to crisp number matrices to investigate their consistency. Several defuzzification methods are presented in literature including distribution, area and maxima methods. Leekwijck and Kerre [20] provided detailed analysis concerning the various defuzzification methods where maxima methods were found more suitable for fuzzy reasoning systems including selection, and distribution and area methods yielded better performance for embedded fuzzy controller applications. Chang defuzzification method [21] takes the risk preference and risk tolerance into account which is denoted by α and λ respectively. Both α and λ are tradeoff parameters between the left and the right bounds; which can closely express the fuzzy perception. The parameter α; $0 \le \alpha \le 1$, is related to the degree of uncertainty; values of α are set to 0, 0.1, 0.2,..., 1 to closely estimate level of uncertainty, and can be expressed as a stable or fluctuating condition so when the environment of the decision-maker is more stable the value of α is higher, when $\alpha = 0$ the degree of uncertainty is greatest and to address a steady environmental uncertainty, α is set to 0.5. Higher values of α will shrink the TF number from both sides towards its highest value. The risk tolerance parameter λ refers to the degree of pessimism where lower values of λ mean the expert is optimistic and the expert census is simply the upper bound, $\lambda = 0$, of the TF number. In contrast, high λ values refer to pessimism and the defuzzified value will be the lower bound when $\lambda = 1$, and to emulate in between state of mind of a decision-maker, the value of λ is set to 0.1, 0.2, 0.5, 0.7, or 0.9 [22]. To address a fair risk attitude, we set λ to 0.5 which entails that the attitude of decision-makers is fair. For a fuzzy number $\tilde{a}_{ij}$, the defuzzified value can be represented as:

$$a_{\mathrm{ij}}^{\alpha,\lambda} = \left[\left(\lambda \times l_{\mathrm{ij}}^{\alpha}\right) + \left(1-\lambda\right)u_{\mathrm{ij}}^{\alpha}\right], 0 \le \lambda \le 1 \text{ and } 0 \le \alpha \le 1 \tag{9}$$

where, $l_{ij}\alpha = (m_{ij} - l_{ij}) \times \alpha + l_{ij}$ and $u_{ij}\alpha = u_{ij} - (u_{ij} - m_{ij}) \times \alpha$ are the left-end and right-end values of the α-cut, respectively.

When all TFNs are converted to crisp numbers (defuzzified values) which equal half of the triangular area using previous equations, the aggregated relationship fuzzy comparison matrix from all decision-makers can be represented as:

$$A^{\alpha,\lambda} = \left[a_{\mathrm{ij}}^{\alpha,\lambda}\right], \forall i = 1,\ldots,n. \forall j = 1,\ldots,n. = \begin{bmatrix} 1 & a_{12}^{\alpha,\lambda} & \cdots & a_{1n}^{\alpha,\lambda} \\ a_{21}^{\alpha,\lambda} & 1 & \cdots & a_{2n}^{\alpha,\lambda} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1}^{\alpha,\lambda} & a_{n2}^{\alpha,\lambda} & \cdots & 1 \end{bmatrix} \tag{10}$$

2.3. Chang's method

Fig. 2 presents the AHP tree with the goal set to select the best RO membrane, criteria, sub-criteria, and lists of alternatives. For each branch of the tree, an aggregate weight has to be found via a squared pair-wise comparison matrix which lists the importance of each criterion as compared to the remaining criteria. The traditional AHP approach implements the idea of pair-wise comparison with crisp values presented in Table 3 that are proposed by Saaty [23]. By deploying the weights down to the alternatives, the scores of the alternatives can be found. The following steps summarize Chang's FAHP method:

Table 3
Crisp values of Saaty scale

Linguistic scale	Equivalent number scale	Reciprocal number scale
Equal important	1	1
Moderate important	3	1/3
Strong important	5	1/5
Very strong important	7	1/7
Extreme important	9	1/9

Step 1: Given a fuzzy matrix, $\widetilde{M}$ which represents the evaluations of any sub-tree, the fuzzy normalized sum of rows can be found as follows

$$\widetilde{M} = \begin{bmatrix} (1,1,1) & (l_{12},m_{12},u_{12}) & \cdots & (l_{1n},m_{1n},u_{1n}) \\ (l_{21},m_{21},u_{21}) & (1,1,1) & \cdots & (l_{2n},m_{2n},u_{2n}) \\ \vdots & \vdots & \vdots & \vdots \\ (l_{n1},m_{n1},u_{n1}) & (l_{n2},m_{n2},u_{n2}) & \cdots & (1,1,1) \end{bmatrix} \tag{11}$$

- Find the row sums (RS) of all fuzzy numbers, RS:

$$\mathrm{RS}_i = \left(l_i^{\mathrm{rs}}, m_i^{\mathrm{rs}}, u_i^{\mathrm{rs}}\right) = \left(\sum_{j=1}^{n} l_{\mathrm{ij}}, \sum_{j=1}^{n} m_{\mathrm{ij}}, \sum_{j=1}^{n} u_{\mathrm{ij}}\right) \tag{12}$$

which will result in a column vector of fuzzy numbers that have a size of n, where n is the size of the evaluation matrix.

- Find the reciprocal of the fuzzy numbers of RS by dividing each of the fuzzy elements above by the sums of all lower, middle and maximum values:

$$S_i = \left(\frac{l_i^{\mathrm{rs}}}{\sum_{i=1}^{n} u_i^{\mathrm{rs}}}, \frac{m_i^{\mathrm{rs}}}{\sum_{i=1}^{n} m_i^{\mathrm{rs}}}, \frac{u_i^{\mathrm{rs}}}{\sum_{i=1}^{n} l_i^{\mathrm{rs}}}\right) = \left(\frac{\sum_{j=1}^{n} l_{\mathrm{ij}}}{\sum_{i=1}^{n}\sum_{j=1}^{n} u_{\mathrm{ij}}}, \frac{\sum_{j=1}^{n} m_{\mathrm{ij}}}{\sum_{i=1}^{n}\sum_{j=1}^{n} m_{\mathrm{ij}}}, \frac{\sum_{j=1}^{n} u_{\mathrm{ij}}}{\sum_{i=1}^{n}\sum_{j=1}^{n} l_{\mathrm{ij}}}\right) \tag{13}$$

Step 2: Find the degree of possibility that $S_j \ge S_i$, $S_i = (l_i, m_i, u_i)$ and $S_j = (l_j, m_j, u_j)$, which is denoted by V. Note that the degree of possibility is a scalar measuring the overlap degree between any two fuzzy numbers. The degree of possibility is represented in Eq. (10) and is illustrated in Fig. 3 where $m_j < l_i < u_j < m_i$. Note that if S_j is entirely higher than S_i, then the degree of possibility is 1, on the other hand, if S_j is entirely less than S_i, then the degree of possibility is 0, otherwise, the possibility is given by the height of intersection ($S_i \cap S_j$).

$$V\left(S_j \ge S_i\right) = \text{height}\left(S_i \cap S_j\right) = \begin{cases} 1 & \text{if } m_j \ge m_i \\ 0 & \text{if } l_i \ge u_j \\ \dfrac{l_i - u_j}{\left(m_j - u_j\right) - \left(m_i - l_i\right)} & \text{otherwise} \end{cases} \tag{14}$$

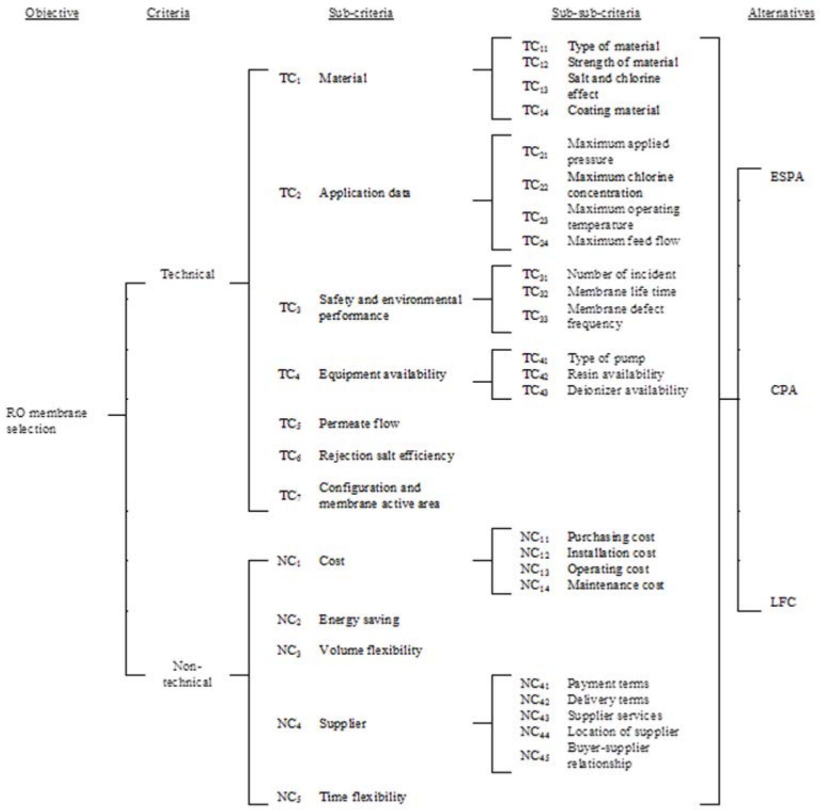

Fig. 2. AHP tree structure

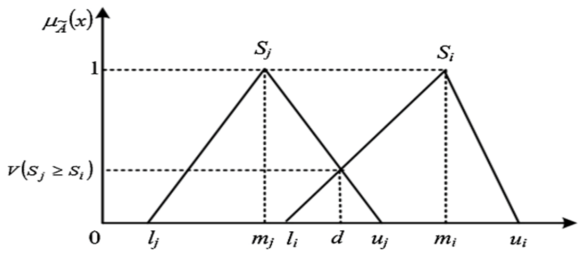

Fig. 3. Intersection between S_i and S_j.

Let the resulting degree of possibility matrix be denoted by:

$$V = \begin{bmatrix} v_{11} & \cdots & v_{1n} \\ \vdots & & \vdots \\ v_{n1} & \cdots & v_{nn} \end{bmatrix} \tag{15}$$

Step 3: Calculate the degree of possibility of S_i over all other n–1 fuzzy numbers, which is simply the minimum value of the rows of the matrix V.

$V(S_j \geq S_i \mid j = 1,\ldots,n;\ j \neq i) = \min$

$$V\left(S_i \geq S_j\right),\ i = 1,\ldots,n,\ j = 1,\ldots,n \text{ and } j \neq i \tag{16}$$

Denote by $d_{\min}$ the vector of row minimums:

$$d_{\min} = \begin{bmatrix} d_1 \\ \vdots \\ d_n \end{bmatrix} \tag{17}$$

Step 4: Find the weight vector W by normalizing $d_{\min}$ through dividing all the elements of $d_{\min}$ by the sum of all elements, such that

$$W_i = \frac{d_i}{\sum_i d_i},\ i = 1,\ldots,n \tag{18}$$

$$W = \begin{bmatrix} W_1 \\ \vdots \\ W_n \end{bmatrix} \tag{19}$$

Note that a weight vector will result in each node in the FAHP tree.

3. Research stages

To build the proposed FAHP model, the study consisted of the subsequent stages illustrated in Fig. 4.

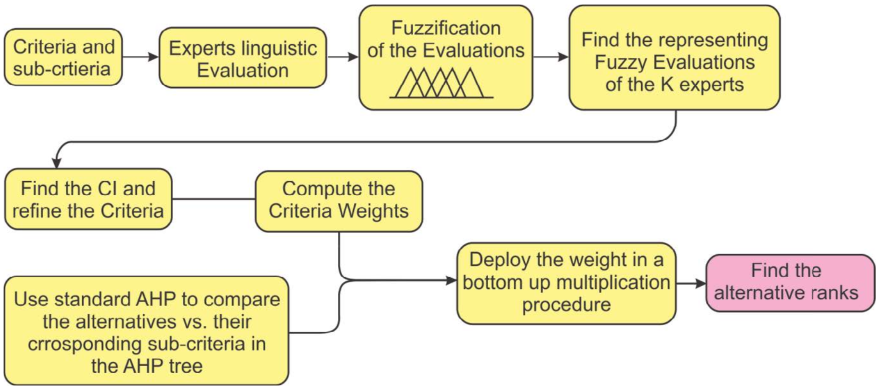

Fig. 4. Schematic diagram of the proposed FAHP model.

3.1. Identification of criteria and alternatives

For this study, a survey questionnaire was developed by the research team based on published literature on desalination processes using membrane technology and selection. The objective of this study was defined as the selection of the best RO membrane to be used in pharmaceutical industries. A set of technical (TC) and non-technical (NC) criteria and sub-criteria for the evaluation process were determined from literature and were validated through interviews with civil, mechanical and chemical engineering academicians from local universities, membrane suppliers and engineers from local pharmaceutical industries. During interviews, each expert was asked to provide judgments based on personal knowledge and expertise. The survey questionnaire was then sent to 20 experts working with membrane technology. Although 15 experts responded, 3 responses were overlooked because the answers were not so logical or consistent; the remaining 12 evaluations were included in this work.

To end up with the set of significant criteria and sub-criteria shown in Table 4, direct relations which assess each criterion without comparing it with the other criteria were acquired in a word-based column to exclude the criteria that are assessed as unimportant (UI) by two thirds (8 experts) or more of the experts. While no non-technical criteria were excluded, the following technical criteria were excluded from further evaluations:

- Type of membrane: the majority of membranes used in the pharmaceutical industry are RO membranes.
- Membrane module: membrane modules are either flat or spiral wounds; the majority of membranes used in the pharmaceutical field are spiral wound membranes.
- Waste production: the waste generated from the membrane process is very low so it is not a significant criterion to be used in the comparison between different membranes.

Chosen criteria are used to select among three alternative RO membranes constructed from polyamide polymer with spiral wound configuration. The first alternative membrane is ESPA1 which is characterized by its energy saving among RO membranes during the filtration processes and produces around 2,100 galloons of permeate flow each day. The second alternative is CPA2 which is known for its high salt rejection and produces around 2,250 gallons of permeate flow each day. The third alternative is LFC3 which is known for its low fouling and produces around 2,100 gallons of permeate flow each day.

3.2. Aggregation of pair-wise comparisons

Using the Kahraman scale as given in Table 1, experts provided pair-wise comparison matrices for selected criteria and sub-criteria. All judgments are aggregated using the AIJ method described earlier. The 12 filled evaluations are reformulated into one representing evaluation; Table A1, see appendix, presents aggregated opinions for technical criteria and non-technical criteria. Aggregated TF numbers are converted to a crisp number using Chang's defuzzification approach and are shown in Table A2 in an appendix for technical and non-technical criteria. Using the MATLAB package, CI and CR are calculated for the matrices and found in the normal range as illustrated in Table 5.

3.3. Finding weights of criteria

The Chang's FAHP method is applied to find the triangular values of the fuzzy synthetic extent (S_i) of all criteria and sub-criteria, the degree of possibility V is constructed and the weight vector W is normalized. The weights of criteria are used to rank criteria based on their importance. Table A3, see appendix, shows the fuzzy synthetic values, Table A4 in the appendix shows a degree of possibility V, and Table 6 shows weights and normalized weights W for technical and non-technical criteria and their sub-criteria.

3.4. Evaluating alternatives

Experts from a local pharmaceutical company are asked to compare the three RO membrane alternatives (ESPA1, CPA2, and LFC3) to criteria and sub-criteria using the Saaty scale presented in Table 2. The resulting weights of all the alternatives to criteria and sub-criteria are computed with the aid of the Expert Choice software package and are shown in Table A5 in the appendix. Using computed weights of criteria and weights of alternatives to criteria, the total weights of alternatives is computed as shown in Table A6, see appendix.

Table 4
Technical and non-technical criteria and sub-criteria

Criteria			Description
TC_1	Material		Degree of the suitability of the chemical, mechanical and permeation properties of the material of the membrane
	TC_{11}	Type of material	Degree of the suitability of the material for safe application
	TC_{12}	Strength of material	Degree of resistance of a material to mechanical stresses
	TC_{13}	Salt and chlorine effect	Degree of the impact of salt and chlorine on material
	TC_{14}	Coating material	Quality of coating material
TC_2	Application data		Degree of the suitability of membrane-based on manufacturer supplied data
	TC_{21}	Maximum applied pressure	The maximum pressure that membrane can tolerate
	TC_{22}	Maximum chlorine concentration	Maximum chlorine concentration that membrane can tolerate
	TC_{23}	Maximum operating temperature	The maximum temperature that membrane can tolerate
	TC_{24}	Maximum feed flow	Maximum flow that membrane can tolerate
TC_3	Safety and environmental performance		Level of safety of membrane to the worker, the product and the environment
	TC_{31}	Number of incident	Number of reported past safety incidents associated with the use of membrane
	TC_{32}	Membrane life time	Estimated time until membrane becomes salvage
	TC_{33}	Membrane defect frequency	History of failure over the lifetime of membrane
TC_4	Equipment availability		Degree of compatibility of the membrane with available desalination process equipment
	TC_{41}	Type of pump	Degree of compatibility with pressure supply by the pump
	TC_{42}	Resin availability	Degree of compatibility with resin equipment
	TC_{43}	Deionizer availability	Degree of compatibility with deionizer
TC_5	Permeate flow		Degree of porosity of membrane to permeate flow and cope with workload
TC_6	Rejection salt efficiency		Percentage of salt rejection in membrane
TC_7	Configuration and membrane active area		An active area of membrane
NC_1	Cost		Initial and operation costs of membrane
	NC_{11}	Purchasing cost	The purchasing cost of membrane
	NC_{12}	Installation cost	The installation cost of the membrane
	NC_{13}	Operating cost	Operating cost over the lifetime of the membrane
	NC_{14}	Maintenance cost	Maintenance cost over the lifetime of the membrane
NC_2	Energy saving		Energy-saving characteristics of the membrane
NC_3	Volume flexibility		Ability to tolerate additional flow during operation
NC_4	Supplier		Quality of characteristics of the supplier of the membrane
	NC_{41}	Payment terms	Financial demands and terms by the supplier
	NC_{42}	Delivery terms	The ability of a supplier to adhere to delivery schedules
	NC_{43}	Supplier services	Availability of additional supplier services
	NC_{44}	Location of supplier	Ease of reach to supplier for prompt shipping
	NC_{45}	Buyer-supplier relationship	History of cooperation with the supplier
NC_5	Time flexibility		Lead time from order to receive

As it was revealed by the experts that technical criteria have more impact on their selection as compared to non-technical criteria, relative weights have been assigned to each group. Particularly, it was agreed to set the weight of the technical criteria to 0.75 and that of the non-technical criteria to 0.25. Accordingly, the final weights of the three alternatives depending on both technical and non-technical criteria are found by summation of the total weights for each alternative as follows:

Alternative 1 (ESPA1) = (0.1987)(0.75) + (0.3832)(0.25) = 0.2448

Alternative 2 (CPA2) = (0.4876)(0.75) + (0.3720)(0.25) = 0.4587

Alternative 3 (LFC3) = (0.3136)(0.75) + (0.2660)(0.25) = 0.3017

4. Results and discussion

The paper presented a group FAHP model for selecting the best RO membrane to be used in desalination processes in the pharmaceutical industry. The research combined theoretical opinions from academia and practical ones from field engineers to select key technical and non-technical criteria. Experts in the field agreed that technical criteria are more important than non-technical criteria with 0.75 and 0.25 relative weights, respectively. The individual fuzzy opinions of experts are aggregated into one Fuzzy pairwise comparison matrix of technical criteria and another for non-technical criteria using the AIJ method. The Chang's FAHP method was then utilized to obtain the weights of seven technical and five non-technical criteria and their corresponding sub-criteria. The lists and rankings of technical and non-technical criteria for the selection of RO membranes are not well established in the literature, a matter that makes this study helpful in applications.

Table 5
Criteria consistency parameter values

Consistency parameters	Technical criteria	Non-technical criteria
Number of criteria (*n*)	7	5
Eigen value	7.664	5.408
Consistency index (CI)	0.111	0.102
Random index (RI)	1.32	1.12
Consistency ratio (CR)	0.084	0.091

Table 6 shows the normalized weights that illustrate the influences of criteria on the final ranking of alternatives. For technical criteria, TC_6 (rejection salt efficiency) has the highest normalized weight of 0.1906 which indicates that has a high impact on selecting the desalination membrane. The rejection salt efficiency (TC_6) is followed by permeate flow (TC_5), application data (TC_2), equipment availability (TC_4), safety and environmental performance (TC_3), material (TC_1) and configuration and membrane-active area (TC_7) with weights of 0.1760, 0.1523, 0.1421, 0.1330, 0.1138 and 0.0921, respectively. For non-technical criteria, NC_1 (cost) has the highest normalized weight of 0.2734 among this group. This result indicates that the presented model is rational since the cost is the most important non-technical criterion, a fact that has been said to be important from the experts' point of view. The following cost (NC_1) ranked order of non-technical criteria includes supplier (NC_4), volume flexibility (NC_3), energy-saving (NC_2) and time flexibility (NC_5) with normalized weights of 0.2244, 0.1889, 0.1850 and 0.1283, respectively. Obtained weights are used to select a better membrane for the pharmaceutical industry.

Obtained weights are utilized to select the best RO membrane among three alternative membrane types widely used in the pharmaceutical industry. Saaty scale was used to pairwise compare three alternative RO membrane types

Table 6
Weights and normalized weights for technical criteria and non-technical and their sub-criteria

Technical criterion	Weights	Normalized weights	Non-technical criterion	Weights	Normalized weights
TC_1	0.5971	0.1138	NC_1	1.0000	0.2734
TC_{11}	1.0000	0.3338	NC_{11}	1.0000	0.3427
TC_{12}	0.9058	0.3023	NC_{12}	0.7779	0.2666
TC_{13}	0.6780	0.2263	NC_{13}	0.5820	0.1994
TC_{14}	0.4121	0.1375	NC_{14}	0.5580	0.1912
TC_2	0.7990	0.1523	NC_2	0.6767	0.1850
TC_{21}	1.0000	0.3528	NC_3	0.6912	0.1889
TC_{22}	0.5792	0.2043	NC_4	0.8209	0.2244
TC_{23}	0.3809	0.1344	NC_{41}	0.8307	0.2023
TC_{24}	0.8747	0.3085	NC_{42}	0.4761	0.1160
TC_3	0.6980	0.1330	NC_{43}	0.8289	0.2019
TC_{31}	0.3128	0.1485	NC_{44}	1.0000	0.2436
TC_{32}	1.0000	0.4747	NC_{45}	0.9699	0.2362
TC_{33}	0.7939	0.3769	NC_5	0.4694	0.1283
TC_4	0.7459	0.1421	Total		1.000
TC_{41}	0.0000	0.0000			
TC_{42}	1.0000	0.5214			
TC_{43}	0.9178	0.4786			
TC_5	0.9237	0.1760			
TC_6	1.0000	0.1906			
TC_7	0.4834	0.0921			
Total		1.000			

(ESPA1, CPA2, and LFC3) to the technical and non-technical criteria and their sub-criteria. Results favored CPA2 which is characterized by a high rejection salt group. CPA2 has a normalized weight of 0.4587 followed by LFC3 with a normalized weight of 0.3017 and ESPA1 with a normalized weight of 0.2448. If only the technical criteria are considered, CPA2 will be most preferred with a normalized weight of 0.4877, while ESPA1 and LFC3 account for the remaining weights of 0.1987 and 0.3136, respectively. On the other hand, if only non-technical criteria are taken into consideration, ESPA1 will be most preferred with a normalized weight of 0.3751 followed by CPA2 and LFC3 with normalized weights of 0.3643 and 0.2606, respectively.

5. Conclusions

Because of the presented model, the following key points could be concluded as a result of developing and applying the FAHP model to the selection of the best membrane in the field of RO technology:

- Experts agreed that technical criteria are more important than non-technical criteria with 0.75 and 0.25 relative weights, respectively.
- For this case study, it was found that the highest-ranked technical criteria for desalination membranes are the rejection salt efficiency and the lowest-ranked one is the active area.
- For non-technical criteria, it was found that the highest-ranked non-technical criterion is the cost while the lowest-ranked non-technical criterion is the time.
- Results show that the percent of salt rejection is the highest-ranked technical criteria with a weight of 0.1906, the cost is the highest-ranked non-technical criteria with a weight of 0.2734 and CPA2 is the most preferred alternative with a total weight of 0.4587.

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Appendix: Intermediate FAHP calculations

Table A1
Aggregated comparison matrix of the technical and non-technical criteria

	TC_1			TC_2			TC_3			TC_4			TC_5			TC_6			TC_7		
TC_1	1	1	1	1/2	1	3/2	2/5	4/7	1	2/5	1/2	2/3	2/7	1/2	3/2	2/7	4/9	2/3	1	17/9	5/2
TC_2	2/3	1	5/2	1	1	1	1/2	14/9	5/2	3/2	2	5/2	1/3	4/7	1	2/5	1/2	2/3	3/2	2	5/2
TC_3	1	16/9	5/2	2/5	2/3	2	1	1	1	2/7	1/2	2	2/5	4/7	1	2/7	1/2	2/3	1	3/2	5/2
TC_4	3/2	2	5/2	2/5	1/2	2/3	1/2	19/9	7/2	1	1	1	2/7	1/2	3/2	2/7	1/2	2/3	1/2	1	2
TC_5	2/3	11/6	7/2	2/3	5/3	3	1	7/4	5/2	2/3	2	7/2	1	1	1	2/5	5/9	1	1	2	7/2
TC_6	3/2	11/5	7/2	1/2	11/6	5/2	1/2	2	7/2	3/2	15/7	7/2	1/2	8/5	5/2	1	1	1	3/2	15/7	7/2
TC_7	2/5	1/2	1	2/5	1/2	2/3	2/5	2/3	1	1/2	1	2	2/7	1/2	1	2/7	1/2	2/3	1	1	1
	NC_1			NC_2			NC_3			NC_4			NC_5								
NC_1	1	1	1	1	2	7/2	1/3	15/8	7/2	3/2	13/6	7/2	1	2	7/2						
NC_2	2/7	1/2	1	1	1	1	2/5	5/8	1	2/5	5/9	5/2	1	5/3	5/2						
NC_3	2/7	1/2	2/3	1	8/5	5/2	1	1	1	2/5	5/8	1	1	5/4	5/2						
NC_4	2/7	1/2	2/3	2/5	16/9	5/2	1	8/5	5/2	1	1	1	1	5/3	52						
NC_5	2/7	1/2	1	2/5	3/5	1	2/5	4/5	1	2/5	3/5	1	1	1	1						

Table A2
Crisp value of the technical and non-technical criteria

Technical criteria (TC)								Non-technical criteria (NC)					
TC	1	2	3	4	5	6	7	NC	1	2	3	4	5
1	1.000	1.000	0.632	0.517	0.718	0.464	1.819	1	1.000	2.096	1.894	2.340	2.145
2	1.321	1.000	1.525	2.000	0.620	0.517	2.000	2	0.584	1.000	0.665	1.006	1.716
3	1.762	0.923	1.000	0.808	0.635	0.472	1.606	3	0.467	1.669	1.000	0.665	1.505
4	2.000	0.517	2.055	1.000	0.709	0.472	1.160	4	0.467	1.616	1.669	1.000	1.716
5	1.963	1.740	1.753	1.995	1.000	0.631	2.145	5	0.567	0.647	0.747	0.647	1.000
6	2.357	1.663	1.976	2.320	1.544	1.000	2.320						
7	0.615	0.517	0.673	1.092	0.567	0.472	1.000						

Table A3
Fuzzy synthetic values

	Technical Criteria			Non-technical criteria		
	L	M	U	L	M	U
S_1	0.043	0.105	0.258	0.1078	0.3186	0.8438
S_2	0.065	0.153	0.369	0.0688	0.1551	0.4500
S_3	0.048	0.112	0.340	0.0822	0.1741	0.4313
S_4	0.049	0.135	0.345	0.0822	0.2296	0.5157
S_5	0.060	0.189	0.525	0.0554	0.1225	0.2813
S_6	0.077	0.226	0.583			
S_7	0.036	0.080	0.214			

Table A4
Degree of possibility $V(S_i \geq S_j)$ for technical and non-technical criteria

	$V(S_i \geq S_j)$ for technical criteria							$V(S_i \geq S_j)$ for non-technical criteria				
ji	1	2	3	4	5	6	7	1	2	3	4	5
1		0.799	0.964	0.873	0.701	0.597	1.000		1.000	1.000	1.000	1.000
2	1.000		1.000	1.000	0.895	0.799	1.000	0.677		0.951	0.832	1.000
3	1.000	0.872		0.928	0.785	0.698	1.000	0.691	1.000		0.863	1.000
4	1.000	0.940	1.000		0.840	0.746	1.000	0.821	1.000	1.000		1.000
5	1.000	1.000	1.000	1.000		0.924	1.000	0.469	0.867	0.794	0.650	
6	1.000	1.000	1.000	1.000	1.000		1.000					
7	0.876	0.673	0.838	0.751	0.586	0.483						

Table A5
Weights of alternatives to criteria and sub-criteria

Technical criterion	Weight (ω) of alternative			Non-technical criterion	Weight (ω) of alternative		
	1	2	3		1	2	3
TC_{11}	0.333	0.333	0.333	NC_{11}	0.669	0.243	0.880
TC_{12}	0.200	0.200	0.600	NC_{12}	0.143	0.429	0.429
TC_{13}	0.333	0.333	0.333	NC_{13}	0.701	0.202	0.097
TC_{14}	0.333	0.333	0.333	NC_{14}	0.600	0.200	0.200
TC_{21}	0.714	0.143	0.143	NC_2	0.701	0.202	0.097
TC_{22}	0.333	0.333	0.333	NC_3	0.086	0.618	0.297
TC_{23}	0.333	0.333	0.333	NC_{41}	0.333	0.333	0.333
TC_{24}	0.091	0.455	0.455	NC_{42}	0.584	0.281	0.135
TC_{31}	0.600	0.200	0.200	NC_{43}	0.327	0.413	0.260
TC_{32}	0.202	0.701	0.097	NC_{44}	0.319	0.460	0.221
TC_{33}	0.202	0.701	0.097	NC_{45}	0.327	0.413	0.260
TC_{41}	0.114	0.481	0.405	NC_5	0.249	0.594	0.157
TC_{42}	0.200	0.600	0.200				
TC_{43}	0.200	0.600	0.200				
TC_5	0.081	0.731	0.188				
TC_6	0.105	0.258	0.637				
TC_7	0.088	0.669	0.243				

Table A6
Total weight of alternatives

Technical criterion	Weight (ω) of alternative			Non-technical criterion	Weight (ω) of alternative		
	1	2	3		1	2	3
TC1	0.0333	0.0333	0.0471	NC1	0.1427	0.0755	0.1295
TC2	0.0598	0.0462	0.0462	NC2	0.1297	0.0374	0.0179
TC3	0.0347	0.0833	0.0149	NC3	0.0162	0.1167	0.0561
TC4	0.0284	0.0853	0.0284	NC4	0.0626	0.0663	0.0425
TC5	0.0143	0.1287	0.0331	NC5	0.0319	0.0762	0.0201
TC6	0.0200	0.0492	0.1214	Total	0.3832	0.3720	0.2660
TC7	0.0081	0.0616	0.0224				
Total	0.1987	0.4876	0.3136				