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Determination of suitable method for solution mining brine recycling using fuzzy analytical hierarchy method

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ABSTRACT

Currently, construction of underground caverns in salt domes using the solution mining technology is a priority among projects for the underground storage of natural gas in Iran. Solution mining in areas with hot and arid climates has not been widely accepted all over the world due the problems with supplying the water required for the salt solution process. Because of the arid and hot climate of the study area, supply of water required for the solution process was one of the most important challenges in this project. In this paper, different scenarios were considered based on the amount of water available for the construction of a cavern with a capacity of 500,000 m^3 using the solution mining. All of the scenarios indicated that in order to construct the aforementioned cavern, the water shortage problem is a major challenge to which solutions shall be prepared before executing the project. In order to resolve this challenge establishment of a desalination plant for recycling the brine resulted from the solution mining process must be considered one of the effective ways returning water to the reuse cycle. Because of the advantages and disadvantages associated with each desalination technology, the selection of the optimum technique for any specific area is a complicated task due to the diversity of objectives and constraints that should be considered and satisfied simultaneously. In this situation where the decision maker confronts many criteria and constraints, multi attribute decision making (MADM) methods can offer a proper solution. The fuzzy analytical hierarchy process (FAHP) is one of the MADM methods utilizing structured pair-wise comparisons. This paper presents an application of the FAHP method to select suitable solution mining brine recycling method. In the proposed FAHP model, fifteen main criteria and four alternatives (desalination technology) are considered. These studies show that such FAHP application can effectively assist engineers to evaluate solution mining brine recycling methods.

Keywords: Solution mining; Underground storage of natural gas; Hot and arid climate; Water supply; Brine recycling; Fuzzy analytical hierarchy (FAHP)

1. Introduction

Currently, Iran is providing the mechanisms required for achieving the solution mining technology by conducting inclusive studies of the storage concept so as to maintain its place in the global competitive markets. Considering the huge reserves of gas in Iran, the recent significant growth of production and consumption of gas in Iran and the world, it is necessary to pay more attention to the downstream issues of the gas industry and make more effort to develop this industry. One of the important downstream issues in this industry is the storage of natural gas. Therefore, construction of underground caverns in salt domes using the solution mining technology is a priority among projects for the underground storage of natural gas in Iran. Currently, the operations for preparation and implementation of some of the projects for the storage of natural gas in depleted fields, aquifers, and salt caverns in Sarajeh (Qom), Yourtishay (Varamin)

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and Nasrabad (Kashan) are being conducted by the Iranian Natural Gas Storage Company (INGSC).

Solution mining is an alternative to mechanical excavation of salt ores. Since most waste components in solution mining are not soluble they ate left behind to settle to the bottom of the expanding caverns as the brine product is removed to surface processing facility [1]. The solution mining process is shown in Fig. 1.

The first step in solution mining salt is to drill an appropriate diameter borehole. Then the caverns are created by pumping out the saturated brine while pumping in fresh water as a controlled production process [2–4]. Solution mining brine concentration is about eight times the normal concentration of seawater [5]. The minerals are then recovered from the saturated fluid by recrystallization. There are several methods for developing and shaping cavern. The most common methods are the direct circulation and reverse circulation method [2].

Many project of salt cavern in the world has been implemented near the sea and where the water resources are high. The target salt dome formation for solution mining in the Iran is situated in a hot and arid climate [6]. Solution mining in areas with hot and arid climates has not been widely accepted all over the world due the problems with supplying the water required for the salt solution process. Evidently, transfer of water to these areas is associated with several problems considering the distance and transmission costs. Moreover, supply of water through aquifers is not a suitable solution for supplying the water required by the solution process due to the high depth and limited volume of the aquifers in the region. Hence, in order to solve the problems associated with water supply various methods were examined. Today, establishment of desalination plant is one of the efficient ways of returning water to the reuse cycle (i.e., recycling water). This technology can probably meet a large part of the need for water in the field of solution mining. Numerous researches have attempted to determine suitable desalination process for drinking water by multi attribute decision making (MADM) methods [7–13]. But solution mining brine recycling in order to water supply requirement have not been considered in the previous studies.

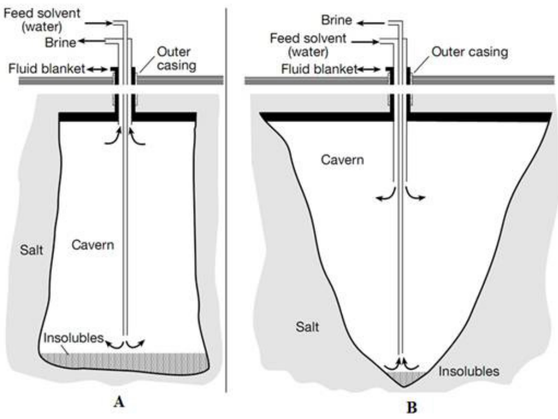

Fig. 1. Solution mining process: (A) Direct circulation, favors lower cavern expansion; (B) Reverse circulation, favors upper cavern expansion) [2].

The aims of the present study are to propose different water supply scenarios for solution mining in Iran and are to determine suitable solution mining brine recycling method using FAHP method in order to water supply requirement. Therefore, according to the authors' knowledge, it is a unique research.

2. Different water supply scenarios

In this research the conditions for excavation of a cavern with 500,000 m^3 volume in the hot and arid climate were studied. First, it is worth noting that from the logical point of view there is an exponential relationship between the increase in cavern volume and cavern construction time. It should be noted that as the cavern volume grows over time the area of the contact surface between water and salt increases and the rate of dissolution and variations of cavern volume also escalate. The increased rate of variations of cavern volume depends on various factors such as the salinity of the dissolution water, the solubility of salt, salt impurities, temperature of circulating water and etc. Therefore, obtaining the exact function of cavern volume changes in terms of time is very difficult and depends on various variables that can vary depending on the excavation platform and the selected method in each region. However, from the technical and economic point of view, as a result of the exponential increase in cavern volume, the potential of equipment of volume of water required for leaching increase exponentially as long as the cavern volume grows. Consequently, toward the final months of the solution process the need for high-capacity desalination equipment for meeting the existing demands is highlighted whereas in the ending days of the cavern excavation operations supply of more advanced equipment is considered uneconomical. Hence, the changes in the early months shall increase with an ascending rate and shall increase at a constant rate afterwards. It is even better to increase the cavern volume with a power lower than the maximum excavation power to increase the factor of safety for timely completion of the cavern excavation process. Investigations revealed that in the observed samples, the average speed of excavation of salt caverns varies in the 100 to 350 m^3/h range. In general, for the excavation of each cubic meter of salt caverns about 6 to 10 cubic meters of fresh water are required [14]. Moreover, each cubic meter of salt produces about eight cubic meters of saturated brine [5]. The main factors determining the growth of a salt cavern and the amount of the resulting brine are directly related to physical (hydraulics and pressure) and physiochemical (temperature and brine concentration) conditions. In this research, in order to dissolve every cubic meter of salt, nine cubic meter of water was used. However, it is worth mentioning that the water in the cavern should not be discharged in the time of excavation. Hence, an amount of water equal to the increase in the cavern volume shall remain in the cavern in each month. As a result, the monthly required volume is assumed to be 10 times the cavern volume in each month.

Therefore, in this study the increase in the cavern volume was defined as an exponential-linear function of time and other influencing factors were not considered. Fig. 2 shows the increase in the cavern volume and the volume of the water required for the solution process in each month. In general, up to the end of the solution mining operations, the required volume water is 10 times the total cavern volume. Hence, to excavate a cavern with a volume of 500,000 m^3, 5 million cubic meters of water is required. The difference between the two curves shows the required amount of water.

The discharge of water flowing into the cavern is determined based on the water supply potential. Sources of water in hot and arid climates include rivers, seasonal lakes or aquifers. However, due to the problem of supplying the urban drinking water near the salt dome area, one of the primary alternatives is to use the urban and industrial effluents and sewage of nearby city. The discharge of water supplied from the aforementioned resources can be assumed 50 L/s on average. Considering the exponential growth rate of cavern volume and the constant discharge of feed water, the volume of the fresh water is expected to be adequate for the expansion of the cavern volume in the early months. However, over time the normal water discharge cannot meet the demand of the large volume of the cavern and the water shortage shall be compensated in some way. Although, desalination technologies have often been used to supply the required drinking water from seawater, the technical and economic aspects of using this water for supplying the industrial water required for returning water to the solution mining process shall be discussed. Anyhow, it is necessary to estimate the capacity of the plant for supplying the industrial water required for the solution mining process based on the demand volume and quality. Accordingly, in the following different scenario of the available alternatives are selected and discussed one by one.

2.1. Scenario 1

Under some circumstances, construction of brine recycling technologies for solution mining may be uneconomic for some reasons or the equipment for the construction of such a plant may be unavailable. In any event, it is necessary to be able to predict the duration of cavern leaching without the possibility of brine recycling. Naturally, in such conditions, water shortage increases the time of cavern excavation. In such a case, the final volume of the cavern is assumed to be 500,000 m^3 and the feed water discharge is assumed to be 50 L/s. For these specifications, supply of water will be 130,000 m^3/month, on average. It is worth noting that in the early months, the rate of cavern volume expansions is lower than the final months of the leaching operations. Hence, at the beginning of the operations a considerable amount of water will be excess and cannot be considered in calculating the volume of the water required for leaching. The progress of cavern excavation using the existing water reserves was shown in Fig. 3. As seen in this figure, it is possible to supply the water required for extracting the cavern up to the 5th month or until the cavern volume reaches 23,000 m^3. This volume is almost equal to 5% of the final volume of the cavern. Therefore, excavation of the remaining 477,000 m^3 shall be carried out in accordance with the monthly water discharge of 130,000 m^3. Moreover, excavation of this volume of cavern calls for the supply of almost 4.8 million m^3 of water (in all figures the portion of below the horizontal axis represents the water shortage).

2.2. Scenario 2

A cavern with final volume of 500,000 m^3 was designed for excavation in a hot and arid climate by assuming the supply of normal water with a discharge of 50 L/s and using desalination plant. Fig. 4 shows the volume of water required for cavern excavating, the shortage/excess of water in each month, and the output discharge of the desalination plant for supplying the water required for the dissolution process for 2 years (24 months). According to Fig. 4, in this scenario, by supplying 130,000 m^3 of water per month, excavation of the cavern faces water shortage problems from the ending of the 4th month and will continue until the end of the 22nd month. In order to address this problem it is possible to utilize a desalination plant to supply part of the required water volume.

It is worth noting that the output capacity of the desalination plant depends on the monthly volume of the feed water. Hence, considering a recovery rate of 50% for the desalination

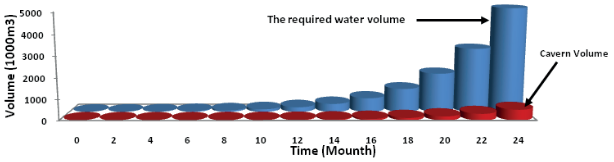

Fig. 2. The rational trend of the growth of cavern volume and the volume of water required for solution process [6].

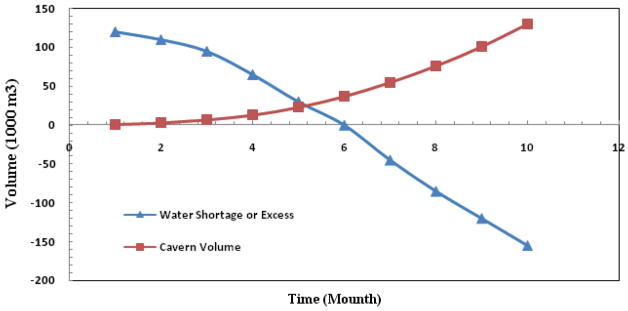

Fig. 3. The progress of the cavern solution process and water shortage or excess supply without desalination plant.

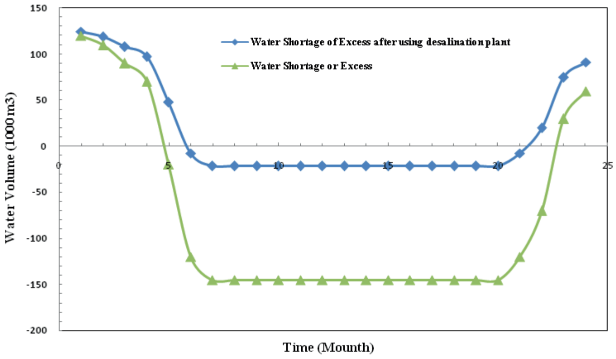

Fig. 4. Water required for excavating a cavern with a discharge of 50 L/s (130,000 m^3/month (V_w)) and using desalination plant.

plant and using the known level of the plant water input per month it is possible to calculate the volume of output water usable in the dissolution process. As seen from Fig. 4, in this case, from the beginning of the 5th month a shortage of water required for salt leaching is observed. However, since in the early months of mining the volume of the existing water is more than the water required for the dissolution operations, it is possible to resolve the water shortage problem provided that the excess water is stored and used in the next months. Even if it is not possible to store the excess water in the early months, it is possible to use the additional amount of water in the last 4 months. Another solution to the problem of water shortage from month 6 onwards to increase the discharge of water to 90 L/s so as to supply the remaining 7,500 m^3 water demand. However, this solution involves special measures and equipment for transferring water since the start of the process. In addition, it is worth mentioning that the desalination process has a continuous cycle. Therefore, if it is possible to carry out the desalination process on the plant output once again, the problem of water shortage can be addressed easily through several stages of desalination. In addition, in the desalination procedure using the reverse osmosis (RO) method the feed water cannot be saturated with salt. Hence, it is necessary to prevent saturation of water with salt by increasing the water circulation speed in the cavern. In this case, it is expected to be able to enter water several times into the desalination cycle. Moreover, the maximum discharge of the desalination plant output is about 4,800 m^3/d (145,000 m^3/month is the maximum volume of water shortage).

2.3. Scenario 3

In this scenario simultaneous excavation of two caverns with an input water discharge of 50 L/s was considered. In case it is necessary to conduct the leaching operations for two caverns (with a volume of 500,000 m^3 for each cavern) simultaneously, the feed water discharge must be divided between the two caverns. Moreover, the desalination plant shall be capable of treating the volume of water required for leaching both caverns. In order to simplify the problem, the total volumes of monthly excavations in both caverns are summed up and it is assumed that the sum of the volumes of both caverns will be obtained with a discharge of 50 L/s. Fig. 5 shows the volume of water required for excavating two caverns an input discharge of 50 L/s. According to Fig. 5, 10 million m^3 of water is expected to be needed to excavate both caverns (which have a total volume of 1 million m^3). However, only part of this volume of water can be supplied and thus, in order to supply the water required for the leaching process it is necessary to utilize other resources or to reuse the existing brine. It is, however, worth noting that the capacity of the desalination plant depends on the volume of the water flowing into the plant. Based on the Fig. 5, the input flow shall have a discharge of 7,000 m^3/d but this volume cannot meet the operational needs. It should be mentioned that the desalination process can be conducted continuously. In other words, if it is not possible to repeat the desalination process for the third or fourth time (or more) it is possible to recover a larger volume of water from the recycling phase and feed it into the leaching process.

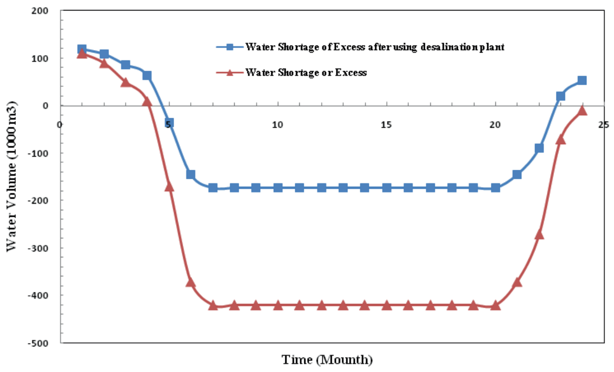

Fig. 5. Water required for excavating two caverns with a discharge of 50 L/s (130,000 m^3/month (V_w)) and using desalination plant.

3. Selection of suitable brine recycling method for water supply requirements

In the previous section, based on different scenarios it was found out that utilization of desalination plant is necessary for recycling the brine produced by the solution mining operations. Numerous brine treatment plant has been founded all over the world [15]. Recycling the brine resulted from solution mining calls for more advanced treatment equipment and expenses because of its high concentration. Therefore, in order to recycle the output brine it is necessary to make changes in the brine recycling process using a low concentration of salt. Various technologies are available for brine desalination. Brine treatment methods are classified into two general categories: membrane methods and thermal methods. The overall classification of these methods is shown in Fig. 6. These methods are generally used for desalination purposes all over the world.

In order to make the decision on the method used for solution mining brine recycling it is necessary to assess and compare the technical, environmental and economic efficiencies of each method. Therefore, the selection and application of a method that can evaluate different criteria and compares them in order to provide suitable alternative for brine recycling is importance. Therefore, in this research a questionnaire has been sent to some experts who are highly experienced in brine treatment and then using fuzzy analytic hierarchy process (FAHP) method, the suitable method for brine recycling has been selected.

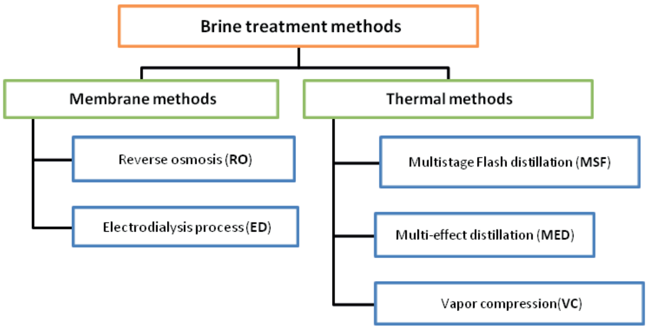

Fig. 6. Different common brine treatment methods [16].

4. Fuzzy analytic hierarchy process (FAHP)

AHP is a multi-criteria decision making (MCDM) method helping decision-maker to face a complicated problem with conflicting and subjective multiple criteria [16]. Among different contexts in which the AHP can be applied, mention can be made from creation of the priorities list, the choice of the best policy, the optimal allocation of resources, the prevision of results and temporal dependencies, and the assessment of risks and planning. Although, the AHP is to capture the experts knowledge, the traditional AHP still cannot really reflect the human thinking style. The traditional AHP method is problematic for using an exact value to express the decision maker opinion in a comparison of alternative [17–20]. Also AHP method is often criticized due to its use of unbalanced scale of judging, its inability to handle the inherent uncertainty and imprecision in the adequate pair-wise comparison process. To overcome all of the shortcomings, FAHP was developed to solve the hierarchical problems. Decision makers usually realize that it is more confident to give interval judgment instead of fixed value judgment. This is because usually he/she is unable to explicit his/her preference to explicit about the fuzzy nature of comparison process [21].

There are various methods proposed for FAHP in literature [22–25]. In this study the extended FAHP is used which was introduced by Chang [26], where $X = \{x_1, x_2, x_3, \ldots, x_n\}$ is object set, and $G = \{g_1, g_2, g_3, \ldots, g_n\}$ is a goal set. According to the Chang's extent analysis method, each object is taken and extent analysis for each goal is performed, respectively. Therefore, "m" extent analysis values for each object can be obtained, with the following equation:

$$M_{gi}^1, M_{gi}^2, \ldots, M_{gi}^m, \quad i = 1,2,3,\ldots,n \tag{1}$$

where $M_{gi}^j = (j-1,2,\ldots,m)$ all are TFN$_s$ (Triangular fuzzy number). The steps of Chang's extent analysis [26] can be given as follows:

Step 1. The value of fuzzy synthetic extent with respect to the i^{th} object is defined as:

$$S_i = \sum_{j=1}^{m} M_{gi}^j \otimes \left[\sum_{i=1}^{n} \sum_{j=1}^{m} M_{gi}^j \right]^{-1} \tag{2}$$

To obtain $\sum_{j=1}^{m} M_{gj}^j$, the fuzzy addition operation of "m" extent analysis values for a particular matrix is performed such as:

$$\sum_{j=1}^{m} M_{gi}^j = \left(\sum_{j=1}^{m} l_j, \sum_{j=1}^{m} m_j, \sum_{j=1}^{m} u_j \right) \tag{3}$$

And to obtain $\left[\sum_{i=1}^{n} \sum_{j=1}^{m} M_{gi}^j \right]^{-1}$, the fuzzy addition operation of $M_{gi}^j \left(j = 1,2,\ldots,m \right)$ values is performed as:

$$\sum_{i=1}^{n} \sum_{j=1}^{m} M_{gi}^j = \left(\sum_{i=1}^{n} l_i, \sum_{i=1}^{n} m_i, \sum_{i=1}^{n} u_i \right) \tag{4}$$

And then the inverse of the vector above is computed, as:

$$\left[\sum_{i=1}^{n} \sum_{j=1}^{m} M_{gi}^j \right]^{-1} = \left(\frac{1}{\sum_{i=1}^{n} u_i}, \frac{1}{\sum_{i=1}^{n} m_i}, \frac{1}{\sum_{i=1}^{n} l_i} \right) \tag{5}$$

Step 2. As $M_1 = (l_1, m_1, u_1)$ and $M_2 = (l_2, m_2, u_2)$ are two triangular fuzzy numbers, the degree of possibility of $M_2 = (l_2, m_2, u_2) \geq M_1 = (l_2, m_2, u_2)$ is defined as:

$$V\left(M_2 \geq M_1\right) = \sup_{y \geq x} \left[\min(\mu_{M_1}(x), \mu_{M_2}(y)) \right] \tag{6}$$

And can be explained as follows:

$$V\left(M_2 \geq M_1\right) = hgt\left(M_1 \cap M_2\right) = \mu_{M_2}(d) \tag{7}$$

$$V(M_2 \geq M_1) = \begin{cases} 1 & \text{if } m_2 \geq m_1 \\ 0 & \text{if } l_1 \geq u_2 \\ \dfrac{l_1 - u_2}{(m_2 - u_2) - (m_1 - l_1)} & \text{otherwise} \end{cases} \tag{8}$$

Fig. 7 illustrates Eq. (8) where "d" is the ordinate of the highest intersection point "D" between μ_{M_1} and μ_{M_2} to compare M_1 and M_2, we need both values of $V(M_1 \geq M_2)$ and $V(M_2 \geq M_1)$.

Step 3. The degree possibility for a convex fuzzy number must be greater than k convex fuzzy $M_i = (i = 1,2,\ldots, k)$ number can be defined by:

$$\begin{gathered} V\left(M \geq M_1, M_2 \ldots, M_k\right) = \\ V\begin{bmatrix} \left(M \geq M_1\right) \text{and} \left(M \geq M_2\right) \\ \ldots\ldots\ldots \text{and} \left(M \geq M_k\right) \end{bmatrix} = \min V\left(M \geq M_i\right) \\ i = 1,2,3,\ldots,k \end{gathered} \tag{9}$$

Assume that $d(A_i) = \min V(S_i \geq S_k)$ for $k = 1, 2, \ldots, n; k \neq i$, then the weight vector is given by:

$$W' = (d'(A_1), d'(A_2), \ldots, d'(A_n))^T \tag{10}$$

where $A_i (i = 1,2,\ldots.,n)$ are n elements.

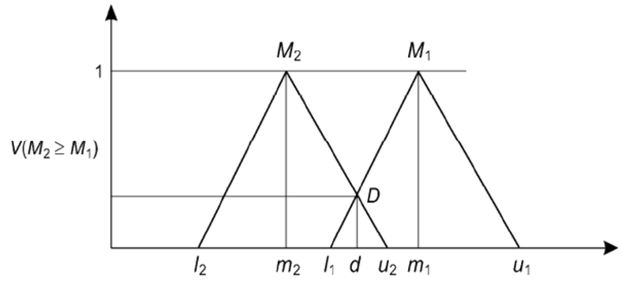

Fig. 7. The intersection between M_1 and M_2 [27].

Step 4. Vianormalization, the normalize weight vector are:

$$W = \left(d\left(A_1\right), d\left(A_2\right), \dots, d\left(A_n\right)\right)^T \tag{11}$$

where W is a non-fuzzy number.

5. Suitable brine recycling method by using FAHP

As mentioned previously, the purpose of this research is the selection of suitable method for solution mining brine recycling using FAHP method. In the first step which is problem structuring, the decision maker states the objectives, defines the selection criteria and picks the alternative choices to be selected from. In the second step, fuzzy techniques are employed and local priorities of selection criteria and alternatives are determined. Finally, in the third step global priorities of each alternative are computed.

For the brine recycling selection using FAHP method, the first step is to build the FAHP diagram that is shown in Fig. 7 which includes the purpose, criteria and alternatives.

In this research we tried to consider all effective factors which influence on the selection of solution mining brine recycling method. Therefore, based on literature review [15,27–30] and engineering judgment, 15 criteria including environment consideration (C1), brine operating temperature range (C2), sensitivity to the feed water quality (C3), need for pre-treatment (C4), feed water salinity range (ppm) (C5), produced water quality (output) (ppm) (C6), obstruction and corrosion potential of facilities (C7), need for maintenance (C8), need for operating skills (C9), availability (localization) (C10), removal of bacterial pollution (C11), mean energy requirement (kWh/m^3) (C12), maximum production capacity (m^3/d) (C13), capital cost (C14) and operation cost (C15) are considered.

Considering the volume and density of solution mining brine, four alternatives including multistage flash distillation (MSF), multi-effect distillation (MED), vapor compression process (VC) and RO have been considered. The process of brine recycling method modeled in a hierarchy as shown in Fig. 8.

Different kind of fuzzy numbers can be utilized for taking the expert's opinion. In this research triangle fuzzy numbers (TFN) have been used. A TFN is denoted simply as (l, m, u). The parameters l, m and u, respectively, denoted the smallest possible value, the most promising value and the largest possible value that describe a fuzzy event.

The first step is to provide a questionnaire which includes main criteria and alternative. This questionnaire has been sent to some experts who are highly experienced in brine treatment. It should be noted that the experts evaluated the importance of criteria base on Saaty's scale [31]. In the next step, FAHP method has been used to calculate the criteria weight and alternatives.

5.1. Determination of criteria's weights

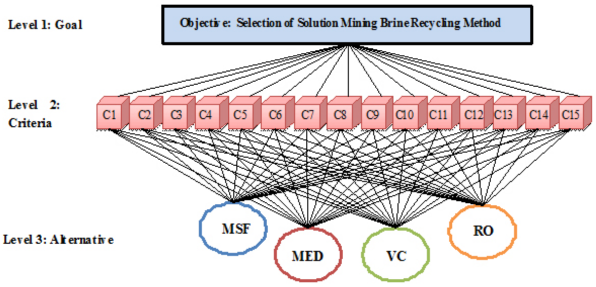

Fig. 8. Hierarchy design for the brine recycling selection process.

Decision makers from different backgrounds may define different weight vectors. They usually cause not only the imprecise evaluation but also serious persecution during the decision process. For this reason, we proposed a group decision based on FAHP to improve pair-wise comparison. Firstly, each decision maker individually carries out pair-wise comparison by using Saaty [31] scale. Then, a comprehensive pair-wise comparison matrix is built by integrating nine decision makers' numbers through Eq. (11) [26]. By this way, decision makers pair-wise comparison values are transformed into triangular fuzzy numbers (Table 1).

After forming fuzzy pair-wise comparison matrix, weights of criteria are determined using FAHP. According to FAHP method, synthesis values must firstly be calculated. From Table 1, synthesis value related to main goal is calculated using Eq. (2).

S_{C1} = (12.238, 22.659, 41.40) ⊗ (1/505.962.1, 1/271.554, 1/142.524) = (0.024, 0.083, 0.290)

S_{C2} = (9.006, 16.853, 31.00) ⊗ (1/505.962.1, 1/271.554, 1/142.524) = (0.018, 0.062, 0.218)

S_{C3} = (3.616, 14.759, 27.971) ⊗ (1/505.962.1, 1/271.554, 1/142.524) = (0.007, 0.054, 0.196)

S_{C4} = (12.416, 19.968, 34.733) ⊗ (1/505.962.1, 1/271.554, 1/142.524) = (0.025, 0.074, 0.224)

S_{C5} = (12.238, 22.613, 43.533) ⊗ (1/505.962.1, 1/271.554, 1/142.524) = (0.024, 0.083, 0.305)

S_{C6} = (6.994, 16.117, 29.4) ⊗ (1/505.962.1, 1/271.554, 1/142.524) = (0.014, 0.059, 0.206)

S_{C7} = (10.575, 16.864, 28. 6) ⊗ (1/505.962.1, 1/271.554, 1/142.524) = (0.021, 0.062, 0.201)

S_{C8} = (8.168, 16.837, 35.667) ⊗ (1/505.962.1, 1/271.554, 1/142.524) = (0.016, 0.062, 0.250)

S_{C9} = (7.343, 16.005, 35.038) ⊗ (1/505.962.1, 1/271.554, 1/142.524) = (0.015, 0.059, 0.246)

S_{C10} = (11.444, 21.990, 41.286) ⊗ (1/505.962.1, 1/271.554, 1/142.524) = (0.023, 0.081, 0.290)

S_{C11} = (3.108, 7.531, 14.867) ⊗ (1/505.962.1, 1/271.554, 1/142.524) = (0.006, 0.028, 0.104)

Table 1
Fuzzy pair-wise comparison matrix

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15
C1	(1, 1, 1)	(0.714, 1.428, 2.333)	(1, 2.259, 9)	(0.714, 1.165, 1.40)	(0.714, 1.020, 1.40)	(0.714, 1.650, 3)	(0.71, 1.36, 1.80)	(0.71, 1.46, 2.33)	0.71, 1.72, 3	(0.71, 1.11, 1.80)	(1.67, 3.68, 7)	(0.71, 1.33, 2.33)	(0.71, 1.17, 1.40)	(0.7, 1.27, 1.80)	(0.71, 1.06, 1.80)
C2	(0.429, 0.807, 1.4)	(1, 1, 1)	(0.556 , 1.558, 5)	(0.600, 0.860, 1)	(0.333, 0.801, 1.40)	(0.429, 1.214, 2.333)	(0.60, 1, 1.40)	(0.56, 1.14, 2.33)	0.33, 1.29, 2.33	(0.43, 0.83, 1.40)	(1.40, 2.82, 7)	(0.71, 0.94, 1)	(0.60, 0.86, 1)	(0.60, 0.94, 1.40)	(0.43, 0.79, 1)
C3	(0.111, 0.693, 1)	(0.2, 0.934, 1.8)	(1, 1, 1)	(0.143, 0.765, 1.28)	0.143, 0.679, 1)	(0.333, 1.004, 1.8)	(0.20, 0.89, 1.80)	(0.11, 1.03, 1.80)	0.33, 1.12, 3	(0.11, 0.77, 1.80)	(0.33, 2.63, 5)	(0.14, 0.90, 1.80)	(0.14, 0.77, 1.29)	(0.20, 0.84, 1.80)	(0.11, 0.74, 1.80)
C4	(0.714, 0.92, 1.4)	(1, 1.207, 1.667)	(0.778, 1.894, 7)	(1, 1, 1)	(0.55, 0.92, 1.40)	(0.714, 1.438, 2.333)	(1, 1.18, 1.40)	(0.71, 1.33, 2.33)	0.56, 1.54, 2.33	(0.56, 0.98, 1.40)	(1.40, 3.41, 7)	(1, 1.12, 1.67)	(1, 1, 1)	(0.71, 1.10, 1.40)	(0.71, 0.92, 1.40)
C5	(0.714, 1.02, 1.4)	(0.714, 1.44, 3)	(1, 2.081, 7)	(0.714, 1.178, 1.80)	(1, 1, 1)	(0.714, 1.578, 3)	(0.71, 1.36, 1.80)	(0.71, 1.48, 2.33)	0.71, 1.67, 3	(0.71, 1.10, 1.80)	(1.67, 3.83, 9)	(0.71, 1.37, 3)	(0.71, 1.18, 1.80)	(0.71, 1.27, 1.80)	(0.71, 1.06, 1.80)
C6	(0.333, 0.783, 1.4)	(0.429, 1.053, 2.33)	(0.556, 1.365, 3)	(0.429, 0.879, 1.400)	(0.333, 0.757, 1.40)	(1, 1, 1)	(0.43, 0.98, 1.40)	(0.33, 1.04, 1.67)	0.60, 1.10, 1.67	(0.33, 0.76, 1)	(0.60, 2.81, 7)	(0.43, 1.01, 2.33)	(0.43, 0.88, 1.40)	(0.43, 0.93, 1.40)	(0.33, 0.77, 1)
C7	(0.556, 0.794, 1.4)	(0.714, 1.04, 1.66)	(0.556, 1.356, 5)	(0.714, 0.873, 1)	(0.556, 0.794, 1.40)	(0.714, 1.201, 2.333)	(1, 1, 1)	(0.56, 1.11, 1.67)	0.56, 1.24, 1.67	(0.56, 0.83, 1.40)	(1.40, 2.82, 5)	(0.71, 0.98, 1.67)	(0.71, 0.87, 1)	(0.71, 0.95, 1.40)	(0.56, 0.79, 1)
C8	(0.429, 0.774, 1.4)	(0.43, 1.068, 1.8)	(0.556, 1.558, 9)	(0.429, 0.886, 1.4)	(0.429, 0.788, 1.40)	(0.600, 1.188, 3)	(0.60, 1.01, 1.80)	(1, 1, 1)	0.56, 1.22, 3	(0.71, 1.11, 1.80)	(1.00, 2.56,5)	(0.43, 0.99, 1.67)	(0.43, 0.89, 1.40)	(0.43, 0.99, 1.80)	(0.43, 0.78, 1)

(Continued)

Table 1 *(Continued)*

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15
C9	(0.333, 0.771, 1.4)	(0.429, 1.083, 3)	(0.333, 1.914, 3)	(0.429, 0.892, 1.8)	(0.333, 0.750, 1.40)	(0.600, 1.017, 1.667)	(0.60, 0.97, 1.80)	(0.33, 1, 1.80)	(1, 1, 1)	(0.43, 0.83, 1.40)	(1.00, 2.78, 9)	(0.43, 1.04, 3)	(0.43, 0.89, 1.80)	(0.43, 0.94, 1.80)	(0.33, 0.75, 1.29)
C10	(0.556, 1.022, 1.4)	(0.714, 1.383, 2.333)	(0.556, 1.356, 9)	(0.71, 1.159, 1.8)	(0.556, 1.016, 1.40)	(1, 1.478, 3)	(0.71, 1.32, 1.80)	(1, 1.39, 2.33)	0.78, 1.58, 3	(1, 1, 1)	(1.00, 3.67, 7)	(0.71, 1.29, 2.33)	(0.71, 1.16, 1.80)	(0.71, 1.23, 1.80)	(0.71, 1, 1.29)
C11	(0.143, 0.352, 0.6)	(0.143, 0.469, 0.714)	(0.2, 2.284, 3)	(0.143, 0.410, 0.714)	(0.111, 0.359, 0.60)	(0.143, 0.581, 1.667)	(0.20, 0.46, 0.71)	(0.2, 0.47, 1)	0.11, 0.57, 1	(0.14, 0.39, 1)	(1, 1, 1)	(0.14, 0.44, 0.71)	(0.14, 0.41, 0.71)	(0.14, 0.45, 0.71)	(0.14, 0.37, 0.71)
C12	(0.429, 0.863, 1.4)	(1, 1.089, 1.4)	(0.556, 0.793, 7)	(0.600, 0.924, 1)	(0.333, 0.877, 1.40)	(0.429, 1.362, 2.333)	(0.60, 1.09, 1.40)	(0.60, 1.24, 2.33)	0.33, 1.44, 2.33	(0.43, 0.90, 1.40)	(1.40, 3.12, 7)	(1, 1, 1)	(0.60, 0.92, 1)	(0.60, 1.01, 1.40)	(0.43, 0.85, 1)
C13	(0.714, 0.920, 1.4)	(1, 1.207, 1.667)	(0.778, 1.825, 7)	(1, 1, 1)	(0.556, 0.927, 1.40)	(0.714, 1.438, 2.333)	(1, 1.18, 1.40)	(0.71, 1.33, 2.33)	0.56, 1.54, 2.33	(0.56, 0.98, 1.40)	(1.40, 3.41, 7)	(1, 1.12, 1.67)	(1, 1, 1)	(0.71, 1.10, 1.40)	(0.71, 0.92, 1.4)
C14	0.556, 0.875, 1.4)	(0.714, 1.131, 1.667)	(0.556, 1.667, 5)	(0.714, 0.949, 1.40)	(0.556, 0.857, 1.40)	(0.714, 1.320, 2.333)	(0.71, 1.10, 1.40)	(0.56, 1.27, 2.33)	0.56, 1.40, 2.33	(0.56, 0.90, 1.40)	(1.40, 3.27, 7)	(0.71, 1.06, 1.67)	(0.71, 0.95, 1.40)	(1, 1, 1)	(0.56, 0.86, 1)
C15	(0.556, 1.015, 1.4)	(1, 1.37, 2.33)	(0.556, 2.254, 9)	(0.714, 1.133, 1.40)	(0.556, 1.022, 1.40)	(1, 1.56, 3)	(1, 1.31, 1.80)	(1, 1.43, 2.33)	0.78, 1.63, 3	(0.78, 1.04, 1.4)	(1.40, 3.79, 7)	(1, 1.27, 2.33)	(0.71, 1.13, 1.40)	(1, 1.22, 1.80)	(1, 1, 1)

Table 2
Large rating of each criteria than other criteria

$V\,(S_x >= S_y)$

	x														
y	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15
C1		0.9	0.855	0.957	0.999	0.883	0.892	0.913	0.900	0.99081	0.589	0.932	0.956	0.932	0.993
C2	1		0.958	1	1	0.986	1	0.999	0.986	1	0.715	1	1	1	1
C3	1	1		1	1	1	1	1	1	1	0.784	1	1	1	1
C4	1	0.944	0.899		1	0.928	0.939	0.951	0.938	1	0.635	0.975	1	0.975	1
C5	1	0.901	0.856	0.957		0.884	0.893	0.913	0.901	0.99143	0.590	0.932	0.957	0.932	0.993
C6	1	1	0.973	1	1		1	1	0.998	1	0.740	1	1	1	1
C7	1	1	0.957	1	1	1		0.999	0.986	1	0.708	1	1	1	1
C8	1	1	0.959	1	1	0.985	1		0.986	1	0.719	1	1	1	1
C9	1	1	0.975	1	1	0.986	1	0.923		1	0.741	1	1	1	1
C10	1	0.911	0.866	0.967	1	1	0.904	1	0.910		0.605	0.942	0.967	0.943	1
C11	1	1	1	1	1	0.895	1	0.974	1	1		1	1	1	1
C12	1	0.97	0.927	1	1	1	0.968	0.951	0.960	1	0.679		1	1	1
C13	1	0.944	0.899	1	1	0.955	0.939	0.972	0.938	1	0.635	0.975		0.975	1
C14	1	0.968	0.925	1	1	0.928	0.966	0.919	0.959	1	0.671	0.998	1		1
C15	1	0.907	0.861	0.964	1	0.953	0.899	0.913	0.9063	0.99737	0.592	0.939	0.963	0.939	
$d'(C_x)$= min	1	0.900	0.855	0.957	0.999	0.883	0.892	0.923	0.900	0.991	0.590	0.932	0.957	0.932	0.993

S_{C12} = (9.337, 18.513, 33.400) ⊗ (1/505.962.1, 1/271.554, 1/142.524) = (0.018, 0.068, 0.234)

S_{C13} = (12.416, 19.968, 34.733) ⊗ (1/505.962.1, 1/271.554, 1/142.524) = (0.025, 0.074, 0.244)

S_{C14} = (10.575, 18.596, 32.733) ⊗ (1/505.962.1, 1/271.554, 1/142.524) = (0.021, 0.069, 0.230)

S_{C15} = (13.051, 22.180, 40.6) ⊗ (1/505.962.1, 1/271.554, 1/142.524) = (0.026, 0.082, 0.285)

These fuzzy values are compared using Eq. (8) and these values are obtained and shown in Table 2:

For example, $V(Sc_3 \geq Sc_1, c_2, \ldots, c_n)$

$$V(S_3 \geq S_1) = \frac{(U_3 - L_1)}{(U_3 - L_1) + (m_1 - m_3)} = 0.855$$

$$V(S_3 \geq S_2) = \frac{(U_3 - L_2)}{(U_3 - L_2) + (m_2 - m_3)} = 0.959$$

$$V(S_3 \geq S_4) = (m_3 \geq m_4) = 0.899$$

$$V(S_3 \geq S_5) = (m_3 \geq m_5) = 0.856$$

$$V(S_3 \geq S_6) = (m_3 \geq m_6) = 0.973$$

$$V(S_3 \geq S_7) = (m_2 \geq m_7) = 0.958$$

$$V(S_3 \geq S_8) = \frac{(U_3 - L_8)}{(U_3 - L_8) + (m_8 - m_3)} = 0.959$$

$$V(S_3 \geq S_9) = \frac{(U_3 - L_9)}{(U_3 - L_9) + (m_9 - m_3)} = 0.975$$

$$V(S_3 \geq S_{10}) = (m_3 \geq m_{10}) = 0.867$$

$$V(S_3 \geq S_{11}) = (m_3 \geq m_{11}) = 1$$

$$V(S_3 \geq S_{12}) = (m_3 \geq m_{12}) = 0.928$$

$$V(S_3 \geq S_{13}) = (m_3 \geq m_{13}) = 0.899$$

$$V(S_3 \geq S_{14}) = (m_3 \geq m_{14}) = 0.925$$

$$V(S_3 \geq S_{15}) = (m_3 \geq m_{15}) = 0.862$$

Table 3
Priority weights for criterion

	Criteria														
	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15
Local weight	1	0.9	0.855	0.957	0.999	0.883	0.892	0.913	0.9	0.991	0.59	0.932	0.957	0.932	0.993
Global weight	0.073	0.066	0.062	0.07	0.073	0.064	0.065	0.067	0.066	0.072	0.043	0.068	0.07	0.068	0.073
Ranking	**1**	11	14	5	**2**	13	12	9	10	4	15	7	6	8	**3**

Priority weight form W' = (1, 0.9, 0.855, 0.957, 0.999, 0.883, 0.892, 0.923, 0.9, 0.991, 0.59, 0.932, 0.957, 0.932, 0.993) vector.

This value must be normalized using Eq. (12).

$$W_i = \frac{W'(C_i)}{\sum_{i=1}^{k} W'(C_i)} \tag{12}$$

After the normalization of these value priorities weight related to main goal are calculated as (0.073, 0.066, 0.062, 0.070, 0.073, 0.064, 0.065, 0.067, 0.066, 0.072, 0.043, 0.068, 0.070, 0.068, 0.073). Mentioned priority weights and ranking have indicated for each criterion in Table 3.

According to the Table 3, it can be seen among the selection criteria, environment consideration (C1), feed water salinity range (C5) and operation cost (C15) are found to be the most important factors affecting the solution mining brine recycling method.

5.2. Ranking of the alternatives

Similarly, the alternative pair-wise comparison matrix into criteria constituted and the final weight of alternative into criteria is obtained which is given in Table 4.

The overall rating of each alternative is calculated by summing the product of the relative priority of each criterion with the relative priority of alternatives considering the corresponding criteria in Table 4.

$$W_{MSF} = (0.073 \times 0.285) + (0.066 \times 0.208) + (0.062 \times 0.337) + (0.070 \times 0.282) + (0.073 \times 0.324) + (0.064 \times 0.263) + (0.065 \times 0.311) + (0.067 \times 0.337) + (0.066 \times 0.076) + (0.072 \times 0.243) + (0.043 \times 0.222) + (0.068 \times 0.037) + (0.070 \times 0.204) + (0.068 \times 0.330) + (0.073 \times 0.043) = 0.233$$

$$W_{MED} = (0.073 \times 0.195) + (0.066 \times 0.208) + (0.062 \times 0.296) + (0.070 \times 0.216) + (0.073 \times 0.3) + (0.064 \times 0.244) + (0.065 \times 0.215) + (0.067 \times 0.333) + (0.066 \times 0.229) + (0.072 \times 0.243) + (0.043 \times 0.222) + (0.068 \times 0.216) + (0.070 \times 0.267) + (0.068 \times 0.175) + (0.073 \times 0.309) = 0.245$$

$$W_{VC} = (0.073 \times 0.253) + (0.066 \times 0.268) + (0.062 \times 0.271) + (0.070 \times 0.264) + (0.073 \times 0.245) + (0.064 \times 0.254) + (0.065 \times 0.102) + (0.067 \times 0.226) + (0.066 \times 0.259) + (0.072 \times 0.252) + (0.043 \times 0.168) + (0.068 \times 0.328) + (0.070 \times 0.295) + (0.068 \times 0.078) + (0.073 \times 0.288) = 0.239$$

$$W_{RO} = (0.073 \times 0.267) + (0.066 \times 0.316) + (0.062 \times 0.096) + (0.070 \times 0.238) + (0.073 \times 0.131) + (0.064 \times 0.239) + (0.065 \times 0.372) + (0.067 \times 0.104) + (0.066 \times 0.437) + (0.072 \times 0.262) + (0.043 \times 0.388) + (0.068 \times 0.419) + (0.070 \times 0.235) + (0.068 \times 0.418) + (0.073 \times 0.360) = 0.283$$

According to abovementioned calculation, the alternative weights and their ranking are shown in Table 5.

Considering the overall results in Table 5, the alternative RO must be selected as the most suitable method for solution mining recycling as the priority of this alternative (0.283) is the highest value comparing others. The second high score belongs to the alternative “MED”.

6. Conclusions

In this study, at the first step, the challenge of supplying water for the construction of a salt cavern in hot and arid area of Iran was studied. Due to the unknown discharge of the available supply of water, three different scenarios were assumed for simultaneous excavation of one and two caverns. Based on these scenarios for water supply requirements, recycling of solution mining output brine is inevitable in all cases. Hence, the output water shall return to the solution mining cycle following treatment. However, in order to do so the output brine shall be collected in special storage ponds since the early months and shall be treated when needed. At the second step, the application of FAHP method for determination of suitable method for solution mining brine recycling was introduced. In the proposed FAHP model, 15 criteria and four alternatives including MSF, MED, VC and RO have been considered. Among the considered brine recycling alternatives, the findings showed that the most suitable brine recycling technology for the case study in this research is RO.

Anyhow, since the monthly shortage of water for cavern leaching operations is highly dependent on the solubility of salt (as a function of increase in cavern volume), it is recommended to specially examine the solubility of salt in the area of concern to be able to obtain a realistic estimation of the rate of increase in cavern volume.

Table 4
Weights between all criteria and alternatives

Alternatives	Criteria															
	C1		C2		C3		C4		C5		C6		C7		C8	
	Local weight	Global weight	Local weight	Global weight	Local weight	Global weight	Local weight	Global weight	Local weight	Global weight	Local weight	Global weight	Local weight	Global weight	Local weight	Global weight
MSF	1.00	0.285	0.66	0.208	1.00	0.337	1.00	0.282	1.00	0.324	1.00	0.263	0.84	0.311	1.00	0.337
MED	0.68	0.195	0.66	0.208	0.88	0.296	0.76	0.216	0.92	0.300	0.93	0.244	0.58	0.215	0.99	0.333
VC	0.88	0.253	0.85	0.268	0.81	0.271	0.93	0.264	0.76	0.245	0.97	0.254	0.27	0.102	0.67	0.226
RO	0.94	0.267	1.00	0.316	0.28	0.096	0.84	0.238	0.40	0.131	0.91	0.239	1.00	0.372	0.31	0.104

Alternatives	Criteria													
	C9		C10		C11		C12		C13		C14		C15	
	Local weight	Global weight	Local weight	Global weight	Local weight	Global weight	Local weight	Global weight	Local weight	Global weight	Local weight	Global weight	Local weight	Global weight
MSF	0.17	0.076	0.93	0.243	0.57	0.222	0.09	0.037	0.69	0.204	0.79	0.330	0.12	0.043
MED	0.52	0.229	0.93	0.243	0.57	0.222	0.52	0.216	0.90	0.267	0.42	0.175	0.86	0.309
VC	0.59	0.259	0.97	0.252	0.43	0.168	0.78	0.328	1.00	0.295	0.19	0.078	0.80	0.288
RO	1.00	0.437	1.00	0.262	1.00	0.388	1.00	0.419	0.80	0.235	1.00	0.418	1.00	0.360

Table 5
Alternative weights

Alternatives	Alternatives weight	Ranking
MSF	0.233	4
MED	0.245	2
VC	0.239	3
RO	**0.283**	**1**

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