Application of analytic hierarchy process for selection of heat transfer meters

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Abstract. At the present time, the process of super-viscous oil deposits development is of current interest among the oil companies. The production of super-viscous oil in the Republic of Tatarstan is carried out using the steam-assisted gravity method. The article proposes a method for solving the problem of selecting a heat meter devices on sites of the Ashalchi field for the production of super-viscous oil. Analytic hierarchy process was used and the parameters required for the optimal selection of heat meters have been determined in the course of investigations. Based on these parameters, a hierarchy for the heat metering unit and a pairwise comparison matrix for the main criteria of the flowmeters have been made. As a result of the analysis, the optimal flowmeter in terms of the chosen criteria has been selected.

1. Introduction

In order to make management decisions and predict possible results, the decision-maker is faced with a complex system of mutually dependent components (resources, desired goals or source material, devices or groups of devices, etc.) that need to be analyzed.

To solve decision-making problems, various mathematical tools of the systems approach are used in various fields. In particular, the universal analytic hierarchy process is now widely used, which interactively allows finding such an alternative that predicts the solution of the problem in the best way. This method (Analytic Hierarchy Process) was proposed by the American scientist Thomas Saaty in 1970, which is rapidly-growing and widely used for comparing objects and solving practical problems of complex control systems. [1]. In order to use this method, it is necessary to systematize large amounts of information; namely, it is necessary to consider several solutions, select a suitable criterion, and determine conditions for problem solving.

The analytic hierarchy process can be presented as the most reasonable solution in a challenging environment of multi-criteria problems with hierarchical structures that include tangible and intangible factors, in contrast to the approach based on linear logic elements. The principle of the method is to divide the problem into simple components by building multi-level hierarchy that combines all the required components, to analyze source data at each level of processing and to compare it. As a result, we get numerical values of the various hierarchy elements interaction, based on which the alternative option is preferred [2, 3].
The main objective of the hierarchy is to evaluate the higher levels at the stage of interaction between different levels of the hierarchy under consideration, and to exclude direct dependence on elements at these levels.

2. Problem statement
Let us review the analytic hierarchy process application when selecting heat meter devices used in the production of super-viscous oil at the Ashalchi field.

The Ashalchi field experimental program has been developed since 2006. The analysis of various thermal treatments for the development of super-viscous oil deposits shows that the most reliable results are obtained when using steam-assisted gravity technology, which includes processes: combination of gravity drainage and steam drive. Based on foreign experience of horizontal wells used for the production of heavy high-viscosity oil, TATNEFT has developed its own technology with the use of paired horizontal wells at a distance of 5-6 m, strictly one above one another. The steam-assisted gravity effect is achieved through a pair of horizontal wells, the upper of which is designed for injecting steam, and the lower for selecting super-viscous oil. Paired horizontal wells are used to drill areas of deposits with an oil-saturated thickness of more than 10-12 meters. Areas of deposits with an oil-saturated thickness of less than 10 meters are drilled with horizontal wells to have a cyclic steam effect.

Saturated vapor is used as a heat-transfer medium on exposure to the steam-assisted gravity. When injecting into the reservoir, the vapor goes up to the roof, making a high-temperature "chamber" and heating the viscous oil. The mechanism of steam drive is that due to the low density of vapor compared to other phases, the "steam chamber" expands upwards and sideward. Discharge vapor runs to the upper part of the reservoir. At the boundary of the "steam chamber", the vapor is condensed in the process of thermal energy transfer to the environment, and the heated oil is driven out by the condensed vapor and flows down under its own weight in the top-down direction. The "steam chamber" space expands as long as the movable oil and condensed vapor are taken from its base [4].

Thus, the increase in reservoir recovery in the process of steam injection is achieved by reducing the oil viscosity, which helps to improve the reservoir coverage.

Oil is always in contact with a high-temperature "steam chamber", i.e. heat losses are minimal, which makes this method profitable from an economic point of view [5].

The steam used for injection is generated by several boiler plants. The original working substance for steam generation in boiler plants is water, and the original energy carrier is natural gas. The steam is the main heat-transfer medium in this production technology, a special place is taken by means of its metering and flow rate control of the steam injected into injection wells. The energy efficiency of this technology is largely determined by the measurement accuracy, which depends on both the metering principle and the quality of the steam flowmeter.

Measuring steam flow rate is a very specific task. It is primarily determined by the parameters of the heat-transfer medium in the steam pipelines: by high temperatures and pressure. The vortex flow meters are the most common among the available devices for measuring the flow rate of heat-transfer fluid.

3. Theory
Suppose we have a number of alternatives (solutions): \( B_1, B_2, \ldots, B_k \). Each of the alternatives is evaluated by a list of criteria: \( K_1, K_2, \ldots, K_n \). The criteria are compared in pairs. The result can be represented as an antisymmetric matrix. The matrix element \( a_{ij} \) is the intensity of hierarchy element \( i \) relative to the hierarchy element \( j \). For pairwise comparison, the author of the Saaty method proposed a special rating scale consisting of five main and four intermediate judgments:

- equal superiority – 1;
- moderate superiority – 3;
• a significant superiority – 5;
• strong superiority – 7;
• very strong superiority-9;
• Even-numbered scores are given in intermediate cases: 2, 4, 6, 8.

Then a matrix is made. In the process of filling the matrix, if element \( i \) is more important than element \( j \), then the cell \((i, j)\) corresponding to row \( i \) and column \( j \) is filled with an integer, and the cell \((j, i)\) corresponding to row \( j \) and column \( i \) is filled with a reciprocal number (fraction).

In addition, pairwise comparison of options for each criterion is performed in the same way as it was done for the criteria, and the corresponding tables are filled in. For each table, the consistency of local priorities is checked by measuring three characteristics [6, 7].

Let us review three types of vortex flow meters that are most frequently used in the Ashalchi field. It is necessary to select the optimal flowmeter in the cost-efficiency ratio and to determine the parameters for the most appropriate option.

4. Experimental results

Let us build a hierarchy for the heat metering unit from the top through intermediate criteria to the lower level (Figure 1).

![Figure 1. Hierarchy for the heat metering unit](image)

We perform a comparative analysis of each criterion in pairs, using a special rating scale consisting of five main definitions and four intermediate definitions (Table 1).

The relative superiority scale contains the reciprocal values 1/3, 1/5, 1/7, 1/9 and intermediate values 1/8, 1/6, 1/4, 1/2. Since the factors are compared twice with each other in a sequential search of all possible pairs, only the part lying below or above the diagonal is filled in to make up the matrix [8, 9].
We build a symmetric pairwise comparison matrix (Table 2).

| Criteria                                      | Price  | Range of heat transfer medium temperatures | Measurement error | Calibration period | Resistance to hydraulic shocks | The dynamic range of the measurement | Maximum operating pressure | $w^*$  | $w_{norm}$ |
|----------------------------------------------|--------|------------------------------------------|-------------------|-------------------|--------------------------------|--------------------------------------|----------------------------|--------|------------|
| Price                                        | 1      | 2                                        | 3                 | 4                 | 5                              | 7                                   | 3                         | 3.06   | 0.306      |
| Range of heat transfer medium temperatures    | 1/2    | 1                                        | 5                 | 5                 | 5                              | 7                                   | 5                         | 3.00   | 0.300      |
| Measurement error                            | 1/3    | 1/5                                      | 1                 | 5                 | 5                              | 7                                   | 5                         | 1.78   | 0.178      |
| Calibration period                           | 1/4    | 1/5                                      | 1/5               | 1                 | 2                              | 5                                   | 2                         | 0.79   | 0.079      |
| Resistance to hydraulic shocks               | 1/5    | 1/5                                      | 1/5               | 1/2               | 1                              | 5                                   | 4                         | 0.7    | 0.070      |
| The dynamic range of the measurement         | 1/7    | 1/7                                      | 1/7               | 1/5               | 1/5                            | 1                                   | 2                         | 0.30   | 0.030      |
| Maximum operating pressure                   | 1/3    | 1/5                                      | 1/5               | 1/2               | 1/4                            | 1/2                                 | 1                         | 0.36   | 0.036      |
| Total                                        | 2.75   | 3.94                                     | 9.74              | 16.20             | 18.45                          | 32.50                                | 22                        | 9.99   | 0.999      |

Let’s measure parameters: standardized priority vector, maximum Eigen value, consistency index. The value of the native factor $w^*$ is determined by the formula:

$$
w^* = \sqrt[n]{a_1 \cdot a_2 \cdot a_3 \cdots a_n},
$$

where $a_j$ - coefficients of the symmetric pairwise comparison matrix $j=0...n$; $n$ - dimension of the symmetric matrix.
The standardized priority vector is determined by the formula:

\[ w_i^* = \frac{w_i}{\sum_{j=1}^{n} w_j^*} \] (2)

The maximum eigenvalue of the considered symmetric matrix (Table 2):

\[ \lambda_{\text{max}}^* = 2.75 \cdot 0.306 + 3.94 \cdot 0.3 + 9.74 \cdot 0.178 + 16.2 \cdot 0.079 + 32.5 \cdot 0.03 + 22 \cdot 0.036 = 8.08 \]

We check if the condition is met:

\[ \lambda_{\text{max}}^* \geq n, \] (3)

This condition is met: 8.08>7.

The consistency index is calculated using the formula:

\[ I_c = \frac{\lambda_{\text{max}}^* - n}{n-1}, \] (4)

\[ I_c = \frac{8 - 7}{6} = 0.18 \]

Given that \( I_c < 0.2 \), the discrepancy between the real and ideal comparison schemes is within the allowed range, so the consistency condition is met.

At the next stage of solving the problem of choosing a flowmeter, we make up pairwise comparison matrix of parameters according to the reviewed criterion (Table 3-9).

### Table 3. "Price" comparison matrix

| Device | 1   | 2   | 3   | \( w^* \) | \( w^* \) norm |
|--------|-----|-----|-----|-----------|----------------|
| 1      | 1   | 1/5 | 1/7 | 3.27      | 0.739          |
| 2      | 1/5 | 1   | 1/2 | 0.74      | 0.167          |
| 3      | 1/7 | 1/2 | 1   | 0.41      | 0.093          |
| Total  | 1.34| 6.50| 10  | 4.42      | 0.999          |

The maximum eigenvalue of the reviewed symmetric matrix (Table 3):

\[ \lambda_{\text{max}}^* = 1.34 \cdot 0.739 + 6.5 \cdot 0.167 + 10 \cdot 0.093 = 3.01. \]
We check if condition (3) is met. Given that $3.01 > 3$, the condition is met. The consistency index is determined by the formula (4): $I_c = 0.005 < 0.2$.

**Table 4.** "Range of heat transfer medium temperatures" comparison matrix

| Device | 3 | 1 | 2 | $w^*$ | $w^*_{\text{norm}}$ |
|--------|---|---|---|-------|-----------------|
| 3      | 1 | 5 | 7 | 3.27  | 0.700           |
| 1      | 1/5| 1 | 7 | 1.12  | 0.240           |
| 2      | 1/7| 1/7| 1| 0.27  | 0.058           |
| Total  | 1.34| 6.14| 15| 4.66  | 0.998           |

According to Table 4: $\lambda_{\text{max}}^* = 1.34 \cdot 0.700 + 6.14 \cdot 0.240 + 15 \cdot 0.058 = 3.28 > 3$. $I_c = 0.14 < 0.2$.

**Table 5.** "Measurement error" comparison matrix

| Device | 3 | 1 | 2 | $w^*$ | $w^*_{\text{norm}}$ |
|--------|---|---|---|-------|-----------------|
| 3      | 1 | 2 | 2 | 1.59  | 0.494           |
| 1      | 1/2| 1 | 2 | 1    | 0.311           |
| 2      | 1/2| 1/2| 1| 0.63  | 0.196           |
| Total  | 2 | 3.50| 5| 3.22  | 1.000           |

According to Table 5: $\lambda_{\text{max}}^* = 2 \cdot 0.494 + 3.5 \cdot 0.311 + 5 \cdot 0.196 = 3.06 > 3$. $I_c = 0.03 < 0.2$.

**Table 6.** "Calibration period" comparison matrix

| Device | 3 | 1 | 2 | $w^*$ | $w^*_{\text{norm}}$ |
|--------|---|---|---|-------|-----------------|
| 3      | 1 | 2 | 2 | 1.59  | 0.485           |
| 1      | 1/2| 1 | 3 | 1.14  | 0.348           |
| 2      | 1/2| 1/3| 1| 0.55  | 0.168           |
| Total  | 2 | 3.33| 6| 3.28  | 1.000           |

According to Table 6: $\lambda_{\text{max}}^* = 2 \cdot 0.485 + 3.33 \cdot 0.348 + 6 \cdot 0.168 = 3.14 > 3$. $I_c = 0.07 < 0.2$.

**Table 7.** "Resistance to hydraulic shocks" comparison matrix

| Device | 1 | 2 | 3 | $w^*$ | $w^*_{\text{norm}}$ |
|--------|---|---|---|-------|-----------------|
| 1      | 1 | 2 | 2 | 1.59  | 0.494           |
| 2      | 1/2| 1 | 2 | 1    | 0.311           |
| 3      | 1/2| 1/2| 1| 0.63  | 0.196           |
| Total  | 2 | 3.5| 5| 3.22  | 1.000           |

According to Table 7: $\lambda_{\text{max}}^* = 2 \cdot 0.494 + 3.5 \cdot 0.311 + 5 \cdot 0.196 = 3.06 > 3$. $I_c = 0.03 < 0.2$.

**Table 8.** "Dynamic range of measurement" comparison matrix

| Device | 1 | 2 | 3 | $w^*$ | $w^*_{\text{norm}}$ |
|--------|---|---|---|-------|-----------------|
| 1      | 1 | 7 | 3 | 2.76  | 0.683           |
| 2      | 1/7| 1 | 1/2| 0.41  | 0.101           |
| 3      | 1/3| 2 | 1 | 0.87  | 0.220           |
| Total  | 1.47| 10| 4.5| 4.04  | 0.943           |

According to Table 8: $\lambda_{\text{max}}^* = 1.47 \cdot 0.683 + 10 \cdot 0.101 + 4.5 \cdot 0.220 = 3$. $I_c = 0 < 0.2$.

**Table 9.** "Maximum operating pressure" comparison matrix
Device | 1 | 2 | 3 | w* | w^*_{norm} |
|------|---|---|---|----|-----------|
| 1    | 1 | 7 | 5 | 3.27| 0.766    |
| 2    | 1/7| 1 | 1/5| 0.3 | 0.070    |
| 3    | 1/5| 5 | 1 | 1   | 0.234    |
| Total| 1.34| 13| 6.20| 4.27| 1.070    |

According to Table 9: $\lambda^*_\text{max} = 1.34 \cdot 0.766 + 13 \cdot 0.070 + 6.2 \cdot 0.234 = 3.38 > 3$. $I_c = 0.19 < 0.2$. 

5. Discussion of results

We have made pairwise comparison matrices for alternative levels. We have determined native factors, standardized vectors, and Eigen values and confirmed the consistency of the matrices. Next, we need to synthesize the final solutions. To do this, we evaluate the standardized vectors with the selected weights of the criteria. As a result, we get the expression:

$$
\begin{pmatrix}
0.739 & 0.240 & 0.311 & 0.168 & 0.494 & 0.683 & 0.766 \\
0.167 & 0.058 & 0.196 & 0.348 & 0.311 & 0.101 & 0.070 \\
0.093 & 0.700 & 0.494 & 0.485 & 0.196 & 0.220 & 0.234
\end{pmatrix}
\times
\begin{pmatrix}
0.005 \\
0.140 \\
0.030 \\
0.070 \\
0.030 \\
0.000 \\
0.190
\end{pmatrix}
= 
\begin{pmatrix}
X_1 \\
X_2 \\
X_3
\end{pmatrix}
= 
\begin{pmatrix}
0.219 \\
0.062 \\
0.198
\end{pmatrix}
$$

The values obtained from the selection of heat flowmeters using the analytic hierarchy process are shown in the Bar chart (Figure 2).

![Figure 2. Bar chart of comparison between heat flowmeters](image)

6. Summary and conclusions

Result analysis shows that the element of the standardized vector $X_1 = 0.219$ has the maximum score. This means that the flowmeter of the first option is the most appropriate in terms of the set of reviewed criteria. We suggest the appropriate solution to the problem of choosing flow meters for heat metering, which allows efficient generation of a system of automation tools.

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