Gray Relational Analysis Optimization for Coalbed Methane Blocks in Complex Conditions Based on a Best Worst and Entropy Method

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Abstract: The uncertainty and complexity of the geological parameters of coalbed methane (CBM) reservoirs may result in the assignment of atypical exact values to a whole block. Therefore, the influence of different resources and productivity characterization indices on the development of CBM blocks was analyzed systematically in this research. Furthermore, this research reported an interval-number index evaluation system and a gray relational analysis optimization model for CBM development. The weights of the evaluation indices were determined by combining the entropy method and the best worst method (BWM) with the objective deviation law of the data and the subjective experience of experts. Based on the gray system theory, a multi-index gray relational analysis optimization model was established to evaluate the interval values and optimize the development potential of CBM blocks with complex geological conditions. The results show that the order of importance of the eight resources and reservoir evaluation indices, from highest to lowest, is permeability, reservoir pressure gradient, gas content, reservoir thickness, reservoir depth, critical reservoir ratio, Young’s modulus, and reservoir temperature. The order of the target blocks, from most to least optimal, is the Sanjiao block, Fanzhuang-Zhengzhuang block, Daning-Jixian block, Gujiao block, and Fengrun block. The evaluation results are consistent with actual conditions. Thus, the multi-index gray relational analysis optimization model, on account of the gray system theory, is feasible for the development evaluation of CBM blocks under complex conditions. This model is suitable for the CBM blocks in the range of 547 km²–675 km². When using this model, the index values must be representative and accurate.

Keywords: CBM block evaluation; combination weight; gray relational analysis; interval-number index

1. Introduction

China’s coalbed methane (CBM) resources are abundant, and more of these resources are developed each year. According to the 13th five-year plan, the production of CBM will reach $2.4 \times 10^{10}$ m$^3$ by 2020. The continued expansion of exploration and development has made the selection and evaluation of CBM blocks increasingly important. The formation conditions of CBM and the evolutionary history of the reservoir structure in China are relatively complex, which leads to the differences in the geological parameters of the same region. The same strata in the same block can have profound differences and complexity, and the exact value is not sufficient to represent the block feature. The selective development of CBM blocks requires a multi-factor evaluation method that is suitable for complex conditions for which the evaluation index is an interval number. The
determination of weights is an important part of the evaluation method and should directly relate to the evaluation results. The method of selecting index weights to avoid subjective assumptions and objective randomness requires further exploration.

Several researchers have proposed relative model methods for block optimization for the geological conditions that are associated with CBM in China. Based on the risk probability and system theory, Ye et al. [1] proposed the idea of “the risk evaluation + analytic hierarchy process (AHP)” and established a “one vote veto + hierarchical optimization” evaluation method system. Zhang et al. [2] followed the dialectical thinking of geological research—quantitative sequencing—geological analysis and established a method system for the evaluation of CBM blocks, which consists of a hierarchical structure optimal selection model, an absolute weight progressive model, and a risk probability model. Areas with high yields and rich concentrations of CBM are expected in some basins of China. Yao et al. [3] proposed a comprehensive evaluation model combined with the AHP and the gray clustering method. This method was used to quantitatively evaluate 121 CBM blocks in China and provide ideas for CBM block evaluation. Li [4] used the AHP to determine the index weights and comprehensively evaluated the favorable CBM blocks in the Ordos Basin by using fuzzy mathematics to identify priority developmental blocks. Several quantitative evaluations of CBM blocks have been performed; however, most of these evaluations directly used existing methods from other fields, and the evaluation indices were mostly fixed values.

The gray system theory emerged as an interdisciplinary approach in 1982 [5]. The gray relational analysis (GRA) is an important aspect of the gray system theory, which measures the degree of closeness between factors according to the sameness or differences in the development trend among the factors. The advantages of GRA in quantitative forecasting and in decision-making based on uncertain and small sample size information attract a large number of researchers. GRA has a wide range of applications, such as those in information technology [6,7], financial markets [8], and industries [9–11]. In addition to these areas, GRA has also been used extensively in the energy fields of various countries. Lee and Lin used 47 office buildings in Taiwan as an example to evaluate and rank their energy performance to illustrate the procedure and effectiveness of the GRA [12]. Akay et al. proposed combining GRA and error propagation theory to select a biofuel and its optimal combustion conditions of South Europe (Spain) [13]. Aslan presented a novel effective method for the optimization of oil agglomeration process of Zonguldak/Turkey bituminous coal with multiple performance characteristics based on the GRA [14]. Adem et al. aimed to identify the optimum parameters affecting the energy and exergy efficiencies for a novel design solar air heater using the gray relational analysis [15].

The geological conditions of CBM reservoirs in China are complex, and the reservoir parameters within one block can have high variability [16,17]. The fixed values of the former index parameters are insufficient to evaluate the selected areas, and thus an interval-number index should be adopted. Assisted by the domestic and international CBM evaluation index system, this research identified reasonable resources and productivity characterization indices to establish an evaluation index system suitable for the complex conditions associated with CBM development in China. The combined weights of the evaluation indices were determined by the best worst method (BWM) and the entropy method. Using the interval evaluation method of the gray relational analysis, the gray relational analysis selection model was established to quantitatively evaluate five CBM target blocks with the areas of 547 km²–675 km², and optimal sorting was carried out.

2. Establishment of an Evaluation Index System for CBM Development

2.1. Index System Construction

Coal is both the source rock and reservoir rock of CBM, which has the dual role of hydrocarbon generation and gas migration [18,19]. Therefore, the evaluation of a CBM reservoir involves not only resource characteristic parameters (e.g., reservoir thickness and gas content) but also production characteristic parameters (e.g., reservoir pressure gradient and permeability).
According to the conditions of CBM reservoirs in China, referring to the evaluation index system of CBM blocks at home and abroad, and avoiding the superposition among various factors, eight resources and productivity characterization indices were selected as the main indices of block development.

(1) Reservoir depth. Reservoir depth controls the economic value and economic efficiency of CBM reservoirs, and this factor affects whether a reservoir has commercial developmental value. It has been known that, as the reservoir depth increases until critical depth, the gas content of CBM increases [20]. However, the permeability of the reservoir decreases continuously [21], which has a negative effect on the seepage and drainage pressure of the CBM well. As a result, the reservoir depth is a cost-type index in reservoir evaluation;

(2) Gas content. Gas content is a key index that simultaneously determines the level of CBM resources abundance and controls the CBM enrichment and production [22]. Along with the increasing of the gas content, the critical desorption pressure and the effective desorption area increased. Therefore, the shorter gas breakthrough time resulted in enhanced gas production per well [23,24]. Obviously, the gas content serves as a profit-type index for reservoir evaluation;

(3) Reservoir thickness. As the source rock and storage space of CBM, a thick enough reservoir thickness is a prerequisite for the enrichment, development, and production of CBM [25,26]. Theoretically, the thicker the reservoir, the more CBM will flow into the wellbore. That is to say, the thick coal seam can provide continuous and sufficient gas source for gas wells and ensure a longer production cycle and higher gas production [27]. Consequently, reservoir thickness is regarded as a profit-type index in the evaluation model;

(4) Reservoir pressure gradient. The reservoir pressure gradient is the main driving force of water flow [28]. In CBM wells, gas is produced mainly by water pressure transmission and the effective drainage radius for reservoir presents a depressurization funnel trend. The greater reservoir pressure gradient resulting in the stronger force of the water flow, the greater the distance of the water pressure transfer, which is more favorable for gas production [29]. For this reason, the reservoir pressure gradient is a profit-type index for reservoir evaluation;

(5) Ratio of critical desorption pressure to reservoir pressure (hereinafter referred to as “critical reservoir ratio”). The critical reservoir ratio represents the dynamic features of CBM desorption, diffusion, and seepage to the bottom of the well. Chen and Yang found that with the increase of the critical reservoir ratio, the gas saturation in the reservoir increased. Then the stronger methane power field made gas evolution under the same declining pressure more easily [30,31]. It was also found that a higher critical reservoir ratio shortened the time of CBM well drainage, which reduced the damage caused by effective stress on the permeability of reservoir during the drainage and depressurization stage, weakened the negative effect of fracturing fluid on critical desorption pressure of reservoir, and increased the aerodynamic force [32,3]. The critical reservoir ratio is considered to be a profit-type index for reservoir evaluation;

(6) Permeability. The reservoir permeability represents the development degree of pores and fractures in coal seam and influences the degree of the gas flow in effective pores of the coal seam [23,33]. Permeability not only regulates the output efficiency of CBM but also affects the radius of the drainage and depressurization funnel in the CBM well [34]. Theory and practice have confirmed that permeability is one of the important reservoir indices for controlling CBM output [35,36]. As a result, permeability is the profit-type index of reservoir evaluation;

(7) Reservoir temperature. Reservoir temperature is an important factor that influences CBM adsorption, desorption, and seepage [37]. As the temperature increased, the molecular energy, thermal activity, and desorption rate of CBM increased [38]. Especially at the later stage of stress unloading, the coalbed has been fully deformed under the influence of temperature [39]. At this time the molecules desorbed from the surface of the matrix are increasing, which will extend the gas production capacity of the CBM well. The reservoir temperature is regarded as a profit-type index in the evaluation model;
Young’s modulus. Young’s modulus represents the degree of deformation caused by stress, which can better reflect the stress-strain characteristics of rock [40]. Young’s modulus is positively correlated with crack height and negatively correlated with crack length and crack width. There are significant differences in the elastic modulus between coal seam and roof and floor rock, which makes the fractures induced by hydraulic fracturing in CBM wells different from conventional hydraulic fracturing. The larger the Young’s modulus difference, the larger the minimum horizontal principal stress difference between the layers, and the formed fractures are more easily controlled in the coal seam [41]. As a result, Young’s modulus is a cost-type index for reservoir evaluation.

2.2. Selection of CBM Development Block Indices

Based on the selected eight resources and productivity characterization indices, the following blocks were selected for this research: The Fanzhuang-Zhengzhuang block in the southern Qinshui coalfield, the Sanjiao block in the central Hedong coalfield, the Gujiao block in the northern Xishan coalfield, the Daning-Jixian block in the southern Hedong coalfield, and the Fengrun block in the southern Ningwu coalfield. Five CBM test blocks, with areas of 547 km² to 675 km², were evaluated as target blocks sorted in the order of Block 1, Block 2, Block 3, Block 4, and Block 5, as shown in Figure 1.

![Figure 1. Shanxi location and target blocks location map.](image)

The main coal seam in Shanxi is the Carboniferous-Permian coal-bearing formation, which occurred mainly during the tectonic movements of the Indosinian, Yanshanian, and Himalayan periods, respectively, among which the Yanshanian period was the most active. The Fanzhuang-Zhengzhuang block is located in the south of Qinshui coalfield, Shanxi Province, and belongs to the groundwater retention area, which provides a suitable hydrogeological condition for the preservation of CBM. The #3 coal seam in the Fanzhuang-Zhengzhuang block has a high degree of thermal evolution, and the degree of metamorphism is in the lean coal-anthracite stage. The coal seam has high gas generating capacity and adsorption capacity, resulting in high gas content. The resource area of the Fanzhuang-Zhengzhuang block is 666 km² and the proved reserves of the CBM
in this block are $861.65 \times 10^8 \text{ m}^3$ [42]. The top and bottom of the coal seam are well-sealed mudstones, which are conducive to the storage of CBM. In this block, the critical reservoir ratio is relatively large, indicating that the desorption pressure is close to reservoir pressure, which shortens the desorption time of CBM, and increases the effective desorption area and production. Because of the large proportion of micropores and small pores in the coal sample, resulting in low permeability [43,44]. However, the widespread development of exogenous fissures makes up for the deficiency of pore development, which causes the CBM of this block to form a high yield, and the average daily gas production per well is $0.2218 \times 10^4 \text{ m}^3$ [45].

The Sanjiao block is a type of gently inclined structure which is located in the middle of the Hedong coalfield, Shanxi Province. The #3 + #4 + #5 coal seam in the Sanjiao block has low permeability mudstone roof strata, which are compact and intact, forming a closed, controlled, tectonic setting, preventing the escape of CBM, and maintaining a high gas content in the coal seam [46]. At the same time, the pores in the coal body are well developed, and the macropore contents are as high as 49.8%, which leads to a relatively high permeability in this area and increases the radius of the drainage and depressurization funnel in the production process of CBM wells, which is conducive to the migration of methane [47]. The resource area of the Sanjiao block is 675 km$^2$, the CBM resource reserve in the main coal seam is $532.7 \times 10^8 \text{ m}^3$, and the average daily gas production per well is $0.24 \times 10^4 \text{ m}^3$ [4,48].

The Gujiao block with an area of 566 km$^2$ is located in the northern part of the Xishan coalfield, Shanxi Province, and the overall structural form is the Malan syncline. Multiple plastic deformations occurred in this block, resulting in a complicated structural shape, serious deformation, and a broken coal body in the #2 coal seam. Multiple stress releases cause the CBM to escape, thus reducing the gas content in the block [49]. The #2 coal in the Gujiao block is mainly bituminous coal of medium metamorphism. The coal quality is soft, and a large amount of pulverized coal can be easily produced under the action of external force, thus blocking the seepage passage, which has an adverse effect on the CBM production [50]. The #2, #8, and #9 coal seams in the Gujiao block all have CBM resources. The proven reserves of CBM resources in the Gujiao block are $820 \times 10^8 \text{ m}^3$, and the average daily gas production per well is $0.065 \times 10^4 \text{ m}^3$ [51].

The Daning-Jixian block with an area of 600 km$^2$ is located in the south of the Hedong coalfield, which belongs to the southern section of the western Shanxi ruffled belt in the eastern part of Ordos Basin. The #5 coal seam mainly formed in the sedimentary environment controlled by the land-based delta, especially in the area between Wucheng-Yaoqu a thick coal-rich belt formed, was conducive to the formation of higher CBM resource abundance. The caprock is dominated by fine sandstone and mudstone with different thickness and great variation. Siltstone and argillaceous sandstone exist locally, which results in medium sealing conditions. The proven reserves of CBM in this block are $295 \times 10^8 \text{ m}^3$ [52]. In this block, the anticline axis of Guyi-Yaoqu is swelled by the structure and the stress is reduced due to the release. The tectonic movement causes secondary fractures and microcracks in the coal seam to develop, which is conducive to the production of CBM, and the average daily gas production per well is $0.2 \times 10^4 \text{ m}^3$ [4].

The Fengrun block with an area of 547 km$^2$ is located in the southern part of the Ningwu coalfield, Shanxi Province, which belongs to the turning end of the complex syncline structure. The immediate roof of the #9 coal seam is mainly composed of sandstone and mudstone, containing a small amount of limestone, and the roof is broken, which leads to the low gas content in this block. The coal seam is in a low-stress zone and is buried relatively shallow. Tensile fissures develop, and the permeability is extremely low, which has an adverse effect on CBM production. The proven reserves of the CBM resources in the Fengrun block are $221 \times 10^8 \text{ m}^3$, and the average daily gas production per well is $0.0729 \times 10^4 \text{ m}^3$ [53,54].

Based on the existing exploration data, the main coal seam evaluation indices for each exploration site in each block were selected. The representative CBM exploration index values were selected as the indicator intervals for evaluation in this research. Specific indicator interval values are shown in Table 1. According to the evaluation index information in Table 1, the average value
and gray standard deviation histogram of the evaluation parameters of target blocks are listed in Figure 2.

Figure 2 shows that, in the evaluation index information of the five target blocks, the four evaluation values in Block 1 have the largest fluctuation values for the reservoir thickness, critical reservoir ratio, permeability, and Young’s modulus, with gray standard deviations of 0.94 m, 0.13, 0.29 × 10⁻³ μm², and 280 MPa. These results show that the occurrence conditions of Block 1 are more variable than those of the other blocks, and the sampling data fluctuate greatly, which leads to instability of the evaluation indices.

**Table 1.** Coalbed methane (CBM) target blocks development evaluation parameter information.

| Category        | Reservoir Depth/m | Gas Content/m³/t | Reservoir Thickness/m | Reservoir Pressure Gradient/MPa/100 m | Critical Reservoir Ratio | Permeability/10⁻³μm² | Reservoir Temperature/°C | Young’s Modulus/MPa |
|-----------------|-------------------|------------------|-----------------------|---------------------------------------|--------------------------|------------------------|--------------------------|------------------------|
| Block 1 (Fanzhuang-Zhengzhuang block) | 230–850          | 14.73–22.80      | 4–9                   | 4.30–9.10                            | 0.45–1.62                | 0.42–3.52              | 21–26                    | 580–1630               |
|             | X = 524           | X = 19.74        | X = 5.50              | X = 5.64                             | X = 0.97                | X = 1.08               | X = 24.60                | X = 1137               |
|             | S = 16            | S = 0.24         | S = 0.94              | S = 1.06                             | S = 0.13                | S = 0.29               | S = 0.69                 | S = 280                |
| Block 2 (Sanjiao block) | 274–393          | 10.67–21.99      | 3–8                   | 4.12–11.47                           | 0.33–1.07                | 1.15–6.27              | 20–35                    | 730–1940               |
|             | X = 341           | X = 12.55        | X = 4.50              | X = 6.61                             | X = 0.43                | X = 2.49               | X = 23.76                | X = 1456               |
|             | S = 7             | S = 0.12         | S = 0.31              | S = 1.60                             | S = 0.04                | S = 0.18               | S = 0.44                 | S = 185                |
| Block 3 (Gujiao block) | 998–1220         | 5.34–20.72       | 2–7                   | 0.11–0.76                            | 0.28–0.74               | 0.02–2.86              | 39–43                    | 1230–3510              |
|             | X = 1092          | X = 7.65         | X = 3.41              | X = 0.64                             | X = 0.31                | X = 1.24               | X = 40.00                | X = 2361               |
|             | S = 20            | S = 0.33         | S = 0.50              | S = 0.05                             | S = 0.01                | S = 0.21               | S = 0.62                 | S = 101                |
| Block 4 (Daning-Jixian block) | 500–1400        | 17.44–18.72      | 6–14                  | 0.81–0.97                            | 0.23–0.61               | 0.01–1.06              | 31–47                    | 1265–3840              |
|             | X = 983           | X = 17.96        | X = 7.59              | X = 0.90                             | X = 0.46                | X = 0.52               | X = 38.00                | X = 2660               |
|             | S = 10            | S = 0.01         | S = 0.69              | S = 0.01                             | S = 0.09                | S = 0.02               | S = 1.87                 | S = 15                 |
| Block 5 (Fengrun block) | 270–819          | 1.25–10.12       | 1–3                   | 0.12–0.94                            | 0.16–0.37               | 0.02–0.12              | 10–28                    | 360–2020               |
|             | X = 494           | X = 8.75         | X = 2.13              | X = 0.71                             | X = 0.30                | X = 0.09               | X = 18.00                | X = 1360               |
|             | S = 20            | S = 1.08         | S = 0.25              | S = 0.12                             | S = 0.01                | S = 0.01               | S = 1.56                 | S = 221                |

Note: X is the average of the index data; S is the gray standard deviation of the index data.

![Figure 2](image)  
**Figure 2.** The average value and gray standard deviation histogram of evaluation parameters of 5 target blocks.
3. Determination of Evaluation Index Weights of CBM Development

The index weight is a numerical value that indicates the relative importance of the indicator. The determination of these weights should include the subjective experience of experts and the objective deviation law of the data. In this research, the index weights used by predecessors in the selection of CBM blocks were considered, and the subjective weight was calculated by the BWM. According to the information entropy of the upper and lower bounds of each evaluation index value, the objective weight value was calculated by the entropy method. The combined weight of each evaluation index value was obtained by integrating the calculation results of the BWM and entropy method.

3.1. Determination of Subjective Weight Based on BWM

The calculation process follows the steps of BWM in reference [55]. The calculation steps are as follows:

Step 1. Select the best criterion (aB) and the worst criterion (aw) among the eight indices, respectively permeability and reservoir temperature;

Step 2. Determine the preference of the best criterion over all the other criteria using a number 1~9. The resulting Best-to-Others vector would be: \( A_B = (a_{B1}, a_{B2}, \ldots, a_{Bn}) \).

The results are shown in Table 2.

| Criteria             | Reservoir Depth | Gas Content | Reservoir Thickness | Reservoir Pressure Gradient | Critical Reservoir Ratio | Permeability | Reservoir Temperature | Young’s Modulus |
|----------------------|-----------------|-------------|---------------------|------------------------------|----------------------------|--------------|-----------------------|-----------------|
| Best criterion:      | 6               | 3           | 5                   | 2                            | 8                         | 1            | 9                     | 7               |
| Permeability         |                 |             |                     |                              |                            |              |                       |                 |

Step 3. Determine the preference of all the criteria over the worst criterion using a number 1~9. The resulting Others-to-Worst vector would be: \( A_W = (a_{W1}, a_{W2}, \ldots, a_{Wn})^T \).

The results are shown in Table 3.

| Criteria             | Reservoir Depth | Gas Content | Reservoir Thickness | Reservoir Pressure Gradient | Critical Reservoir Ratio | Permeability | Reservoir Temperature | Young’s Modulus |
|----------------------|-----------------|-------------|---------------------|------------------------------|----------------------------|--------------|-----------------------|-----------------|
| Best criterion:      | 4               | 6           | 5                   | 8                            | 2                         | 9            | 1                     | 3               |
| Reservoir temperature|                 |             |                     |                              |                            |              |                       |                 |

Step 4. The optimal weight for the criteria is the one where for each pair of \( w_{ji} \) and \( w_{wj} \):

\[
\frac{w_{ji}}{w_{wj}} = a_{ji} \quad \text{and} \quad \frac{w_{wj}}{w_{wj}} = a_{wj}.
\]

For all \( j \), we should find a solution where the maximum absolute differences

\[
\left| \frac{w_{ji}}{w_{wj}} - a_{ji} \right| \quad \text{and} \quad \left| \frac{w_{wj}}{w_{wj}} - a_{wj} \right|
\]

for all \( j \) is minimized. Considering the non-negativity and sum condition for the weights, the following problem has resulted:

\[
\min \xi,
\]

s.t.

\[
(1)
\]
where $a_{Bi}$ indicates the preference of the best criterion B over criterion j, $a_{jW}$ indicates the preference of the criterion j over the worst criterion W, and $\xi$ is a constant.

Solving this model, we have:

$$w^*_1 = 0.0675, \quad w^*_2 = 0.1349, \quad w^*_3 = 0.0810, \quad w^*_4 = 0.2025, \quad w^*_5 = 0.0506, \quad w^*_6 = 0.3671, \quad w^*_7 = 0.0450, \quad w^*_8 = 0.0514,$$

and $\bar{\xi} = 0.84$. The consistency ratio is $a_{BW} = a_{57} = 9$, the consistency index for this problem is 5.23, and the consistency ratio is 0.84/5.23 = 0.16, which implies a very good consistency.

The weight values of reservoir depth, gas content, reservoir thickness, reservoir pressure gradient, critical reservoir ratio, permeability, reservoir temperature, and Young’s modulus determined by the BWM were

$$w_j = (0.0675, 0.1349, 0.0810, 0.2025, 0.0506, 0.3671, 0.0450, 0.0514).$$

### 3.2. Determination of Objective Weight Based on the Entropy Method

The entropy method is an analytical method for determining the weight of the interval index based on the different degree of each interval index. Entropy calculation begins with determining the upper and lower bounds of the information entropy values ($E^+_j$ and $E^-_j$) for the index values of each scheme with different indicators. The deviation degree of each scheme’s index value is reflected by the average value $E_j$ of $E^+_j$ and $E^-_j$. The lower the $E_j$ is, the lower is the degree of disorder that reflects the index information is, and the greater the deviation degree of the interval index value and the importance ($d_j$) of this indicator for block evaluation are; this trend shows that the index weight ($W_j$) is of greater importance [56].

The contribution of the i block under the j index follows (2):

$$P_i = \frac{X_{ij}}{\sum_{j=1}^{m} X_{ij}}, \quad (2)$$

where $X_{ij}$ is the upper and lower bound matrix elements of the various indicators and m is the number of different blocks.

The information entropy of the index values of each scheme under different indicators can be calculated by using (3):

$$E_j = -K \sum_{i=1}^{m} P_j \cdot \ln (P_j), \quad (3)$$

where constant $K = \frac{1}{\ln (m)}$.

The importance of different indices to block evaluation is as follows, in (4):

$$d_j = 1 - E_j \quad (4)$$

The weight of each index can be calculated by using (5):

$$w_j = \frac{d_j}{\sum_{i=1}^{m} d_i} \quad (5)$$
where \( n \) is the number of different indices.

The index weight determined by the entropy method is

\[
W_j = (0.0708, 0.0715, 0.0702, 0.3127, 0.0495, 0.3482, 0.0325, 0.0444).
\]

### 3.3. Determination of Combination Weights

The method of multiplicative composition was used to combine the BWM and the entropy method to determine the weights of the eight indices; the weight of each index was unified with the subjective experience of experts and the objective deviation of the data. The weighted model follows (6):

\[
W_j = \frac{W_{aj} \cdot W_{bj}}{\sum_{j=1}^{n} W_{aj} \cdot W_{bj}}
\]

After normalized treatment, the combined weight of each index is

\[
W_j = (0.0220, 0.0443, 0.0261, 0.2911, 0.0115, 0.5877, 0.0067, 0.0105).
\]

The calculation results of the combined weight for each index suggest that the importance of each index in the optimal selection system of the CBM block is as follows, from greatest to least: permeability, reservoir pressure gradient, gas content, reservoir thickness, reservoir depth, critical reservoir ratio, Young’s modulus, and reservoir temperature. The corresponding respective weights are 0.5877, 0.2911, 0.0443, 0.0261, 0.0220, 0.0115, 0.0105, and 0.0067.

The results show that the permeability and reservoir pressure gradient are two key impact factors that affect the CBM block development, and their weights exceed 20%, especially the weight of permeability, which is more than 50%. The permeability and reservoir pressure gradient play a key role in controlling CBM migration and production. The weights of the gas content, reservoir thickness, reservoir depth, critical reservoir ratio, and Young’s modulus are between 1% and 5%, which indicates that those indices have a moderate influence on CBM development.

### 4. Optimal Selection of CBM Development Blocks

#### 4.1. Optimal Selection of GRA for CBM Blocks Based on Interval Value of the Evaluation Indices

The gray system theory research on the uncertainty system is defined as “some information is known, some information is unknown”. The quantitative data obtained in the CBM selection evaluation are limited and fluctuate, so there is no typical distribution rule. The CBM selection evaluation system is, therefore, a typical gray system, which can be evaluated by the gray system theory. The GRA method is an important part of the gray system theory, and its steps are as follows:

1. Establishment of upper and lower bound matrices

According to the interval evaluation parameters of CBM blocks in Table 1, the upper bound matrix \( \overline{G} \) (7) and lower bound matrix \( \underline{G} \) (8) of the eight evaluation indices are established. The upper bound matrix \( \overline{G} \) (7) is composed of the maximum of each index interval, and the lower bound matrix \( \underline{G} \) (8) is composed of the minimum of each index interval.

\[
\overline{G} = \begin{bmatrix}
\text{Reservoir depth} & \text{Gas content} & \text{Reservoir thickness} & \text{Reservoir pressure gradient} & \text{Critical reservoir ratio} & \text{Permeability} & \text{Reservoir temperature} & \text{Young’s modulus} \\
\text{Block 1} & 850 & 22.80 & 9 & 9.10 & 1.62 & 3.52 & 26 & 1630 \\
\text{Block 2} & 393 & 21.99 & 8 & 11.47 & 1.07 & 6.27 & 35 & 1940 \\
\text{Block 3} & 1220 & 20.72 & 7 & 0.76 & 0.74 & 2.86 & 43 & 3510 \\
\text{Block 4} & 1400 & 18.72 & 14 & 0.97 & 0.61 & 1.06 & 47 & 3840 \\
\text{Block 5} & 819 & 10.12 & 3 & 0.94 & 0.37 & 0.12 & 28 & 2020
\end{bmatrix}
\]

\[
\underline{G} = \begin{bmatrix}
\text{Reservoir depth} & \text{Gas content} & \text{Reservoir thickness} & \text{Reservoir pressure gradient} & \text{Critical reservoir ratio} & \text{Permeability} & \text{Reservoir temperature} & \text{Young’s modulus} \\
\text{Block 1} & 850 & 22.80 & 9 & 9.10 & 1.62 & 3.52 & 26 & 1630 \\
\text{Block 2} & 393 & 21.99 & 8 & 11.47 & 1.07 & 6.27 & 35 & 1940 \\
\text{Block 3} & 1220 & 20.72 & 7 & 0.76 & 0.74 & 2.86 & 43 & 3510 \\
\text{Block 4} & 1400 & 18.72 & 14 & 0.97 & 0.61 & 1.06 & 47 & 3840 \\
\text{Block 5} & 819 & 10.12 & 3 & 0.94 & 0.37 & 0.12 & 28 & 2020
\end{bmatrix}
\]
(2) The establishment of virtual ideal and virtual negative ideal schemes

By establishing a virtual ideal scheme and a virtual negative ideal scheme, the parameters of the block are evaluated close to the virtual reference scheme. The virtual ideal scheme is the optimal scheme for the lower bound matrix \( \mathbf{G} \) (8), whereas the virtual negative ideal scheme is the worst scheme for the upper bound matrix \( \overline{\mathbf{G}} \) (7). The degree of proximity between the evaluation parameters of the CBM blocks and the two virtual reference schemes determines the CBM blocks' development potential.

For the lower bound matrix \( \mathbf{G} \) (8), let \( A = [a_1, a_2, \ldots, a_8] \) be a virtual ideal scheme, where \( a_i \) is the optimal value of the j-th index in the lower bound matrix \( \mathbf{G} \) (8). When the j-th index is a profit-type index, \( a_i = \max G_{ij} \) (0 ≤ I ≤ 5); when the j-th index is a cost-type index, \( a_i = \min G_{ij} \) (0 ≤ I ≤ 5). The virtual ideal scheme is, therefore, \( A = [230, 17.44, 6, 4.3, 0.45, 1.15, 39, 360] \).

For the upper bound matrix \( \overline{\mathbf{G}} \) (7), let \( B = [b_1, b_2, \ldots, b_8] \) be a virtual negative ideal scheme, where \( b_j \) is the optimal value of the j-th index in the upper bound matrix \( \overline{\mathbf{G}} \) (7). When the j-th index is a profit-type index, \( b_j = \min G_{ij} \) (0 ≤ I ≤ 5); when the j-th index is a cost-type index, \( b_j = \max G_{ij} \) (0 ≤ I ≤ 5). The virtual negative ideal scheme is, therefore, \( B = [1400, 10.12, 3, 0.76, 0.37, 0.12, 26, 3840] \).

(3) Normalization of evaluation indices

Since each evaluation index has a different magnitude and dimension, it is necessary to normalize the values for each parameter.

For the lower bound matrix \( \mathbf{G} \) (8), the virtual ideal scheme is used as the reference data column, and the data column in \( \mathbf{G} \) (8) is used as the comparison data column. After normalization of the virtual ideal scheme, it is \( \mathbf{X} = \left[ \begin{array}{cccccccc} \frac{1}{X_1} & \frac{1}{X_2} & \frac{1}{X_3} & \frac{1}{X_4} & \frac{1}{X_5} & \frac{1}{X_6} & \frac{1}{X_7} & \frac{1}{X_8} \end{array} \right] \). For the profit-type index, such as reservoir thickness, gas content, reservoir pressure gradient, critical reservoir ratio, permeability, and reservoir temperature, the normalized formula is \( \frac{1}{X_i} = \frac{a_i}{X_i} \). For the cost-type index, such as the reservoir depth and Young's modulus, the normalized formula is \( \frac{1}{X_i} = \frac{a_i}{X_i} \).

Similarly, for the upper bound matrix \( \overline{\mathbf{G}} \) (7), the normalization of the virtual negative ideal scheme is \( \mathbf{X} = \left[ \begin{array}{cccccccc} \frac{1}{X_1} & \frac{1}{X_2} & \frac{1}{X_3} & \frac{1}{X_4} & \frac{1}{X_5} & \frac{1}{X_6} & \frac{1}{X_7} & \frac{1}{X_8} \end{array} \right] \). For the profit-type index, the normalized formula is \( \frac{1}{X_i} = \frac{b_i}{X_i} \). For the cost-type index, the normalized formula is \( \frac{1}{X_i} = \frac{b_i}{X_i} \).

The normalized evaluation indices of the upper bound matrix \( \overline{\mathbf{G}} \) (7) and lower bound matrix \( \mathbf{G} \) (8) are shown in Table 4.

| Index | Reservoir Depth | Gas Content | Reservoir Thickness | Reservoir Pressure Gradient | Critical Reservoir Ratio | Permeability | Reservoir Temperature | Young's Modulus |
|-------|----------------|-------------|--------------------|---------------------------|------------------------|-------------|----------------------|----------------|
| Block 1 | 0.607 | 1.00 | 0.44 | 0.84 | 0.33 | 0.66 | 0.08 | 1.00 | 0.22 | 1.00 | 0.03 | 0.56 | 1.00 | 0.53 | 1.00 | 0.45 |
| Block 2 | 0.281 | 0.84 | 0.46 | 0.61 | 0.37 | 0.50 | 0.06 | 0.95 | 0.34 | 0.73 | 0.01 | 1.00 | 0.74 | 0.51 | 0.84 | 0.57 |
| Block 3 | 0.871 | 0.23 | 0.48 | 0.30 | 0.42 | 0.33 | 1.00 | 0.50 | 0.62 | 0.04 | 0.01 | 0.60 | 1.00 | 0.46 | 0.97 |
| Block 4 | 1.000 | 0.34 | 0.22 | 1.00 | 0.06 | 0.03 | 0.02 | 0.79 | 0.42 | 1.00 |
(4) Calculation of the correlation degree between the upper bound matrix \( \mathcal{G}(7) \) and lower bound matrix \( \mathcal{G}(8) \) and the virtual positive and negative ideal schemes after standardization

The correlation coefficient \( \xi(j) \) between the j-th index value \( x_{ij} \) of the i-th block of the normalized upper bound matrix \( \overline{\mathcal{G}}(7) \) and lower bound matrix \( \mathcal{G}(8) \) and the j-th index value of the corresponding virtual positive and negative ideal schemes follows (9):

\[
\xi(j) = \frac{\min_{i} \min_{j} [x_{ij}(j) - x_{ij}(j)] + \rho \cdot \max_{i} \max_{j} [x_{ij}(j) - x_{ij}(j)]}{\max_{i} \max_{j} [x_{ij}(j) - x_{ij}(j)]}
\]

where \( x_{ij}(j) \) is virtual positive and negative ideal scheme \([1,1,...,1]\) and \( \rho \) is the resolution coefficient, which represents the size of the comparison environment, \( \rho \in [0,1] \). The lower the \( \rho \) is, the greater the resolution. Generally, 0.5 is used according to the principle of least information, which can improve the difference in the correlation coefficient [57].

The gray correlation coefficient matrices \( \overline{E}(10) \) and \( \mathcal{E}(11) \) of upper and lower bound are obtained as follows:

\[
\overline{E} = \begin{bmatrix}
0.5577 & 0.4712 & 0.4262 & 0.3510 & 0.3909 & 0.3390 & 1.0000 & 1.0000 \\
0.4080 & 0.4785 & 0.4422 & 0.3466 & 0.4311 & 0.3356 & 0.6585 & 0.7559 \\
0.7934 & 0.4918 & 0.4646 & 1.0000 & 0.4977 & 0.3409 & 0.5564 & 0.4804 \\
1.0000 & 0.3367 & 0.3367 & 0.3515 & 0.4418 & 0.3386 & 0.3360 & 0.4624 \\
0.5442 & 1.0000 & 1.0000 & 0.7218 & 1.0000 & 0.8747 & 0.7197 & 1.0000 
\end{bmatrix}
\]

\[
\mathcal{E} = \begin{bmatrix}
0.7617 & 0.5981 & 1.0000 & 0.4383 & 0.5175 & 0.4776 \\
0.7548 & 0.5608 & 0.4977 & 0.6498 & 1.0000 & 0.5043 & 0.5395 \\
0.3925 & 0.4166 & 0.4262 & 0.3572 & 0.5673 & 0.3351 & 1.0000 & 0.9465 \\
0.4785 & 1.0000 & 1.0000 & 0.3790 & 0.5033 & 0.3333 & 0.7074 & 1.0000 \\
0.7700 & 0.3481 & 0.3730 & 0.3370 & 0.4348 & 0.3351 & 0.3998 & 0.4090 
\end{bmatrix}
\]

The degree of correlation between the normalized upper and lower bound matrices and the virtual negative and positive ideal scheme is

\[
\sum_{j=1}^{m} W_{j} \xi_{j}(j) + \sum_{j=1}^{m} W_{j} \xi_{j}(j)
\]

where \( W_{j} \) is the weight of the j-th index.

(5) Determination of the multi-index GRA optimization model

The greater the disparity between the upper bound value of the block to be evaluated and the virtual negative ideal scheme is, the lower the \( \sum_{j=1}^{m} W_{j} \xi_{j}(j) \) and the greater the development potential of the block. The closer the lower bound value of the block to be evaluated is to the virtual ideal scheme, the greater the \( \sum_{j=1}^{m} W_{j} \xi_{j}(j) \) and the greater the development potential of the block. For the evaluation result of the i-th block, the degree of belonging to the virtual negative ideal scheme is \( u_{i} \), the degree of belonging to the virtual ideal scheme is 1-\( u_{i} \), and the multi-index gray relation analysis optimization model is established as follows:

\[
u_{i} = \frac{\sum_{j=1}^{m} W_{j} \xi_{j}(j)}{\sum_{j=1}^{m} W_{j} \xi_{j}(j) + \sum_{j=1}^{m} W_{j} \xi_{j}(j)}
\]
When \( u_i \) is greater, the index parameters of the block are closer to those of the virtual ideal scheme, and the development potential of the block is greater.

4.2. Optimal Selection Results and Discussions

A comprehensive evaluation was performed according to the multi-index gray relation analysis optimization model, and the results are shown in Table 5. Table 5 shows that the ranking of the target blocks from the most to least optimal membership degree is as follows: Block 2 (0.8936), Block 1 (0.7500), Block 4 (0.5123), Block 3 (0.2808), and Block 5 (0.1112). It shows that the development potential of target blocks decreases from the Sanjiao block to the Fanzhuang-Zhengzhuang block, Daning-Jixian block, Gujiao block, and Fengrun block.

| Target Block | Block 1 | Block 2 | Block 3 | Block 4 | Block 5 |
|--------------|---------|---------|---------|---------|---------|
| Optimal membership degree | 0.7500 | 0.8936 | 0.2808 | 0.5123 | 0.1112 |

As shown in Figure 3, in terms of the overall change trend, the average daily gas production per well and the optimal membership degree obtained by the GRA optimization model of the five target blocks show good consistency. However, there is a small difference between the Gujiao block and the Fengrun block in the consistency of average daily gas production per well and optimal membership degree. The difference may be due to the low development level of these two blocks and the small number of CBM wells, which fail to accurately reflect the CBM production capacity of the block.

Figure 3. The trend chart of daily gas production per well and optimal membership degree in CBM blocks.

The above analysis shows that the GRA optimization model based on interval value can be applied to the production potential optimization evaluation of CBM blocks with large changes in reservoir parameters under complex conditions.

5. Conclusions

(1) Within the examined CBM reservoirs, which are associated with complex conditions in China, eight resources and productivity characterization indices, namely, the reservoir depth, gas content, reservoir thickness, reservoir pressure gradient, critical reservoir ratio, permeability, reservoir temperature, and Young’s modulus, were selected as the main evaluation indices of development blocks;
The importance of an evaluation index was determined by the combination of the subjective experience of the experts, the objective deviation of the data through the BWM and the entropy method. The importance of the evaluation indices, ordered from high to low, is permeability, reservoir pressure gradient, gas content, reservoir thickness, reservoir depth, critical reservoir ratio, Young’s modulus, and reservoir temperature, and the weights are 0.5877, 0.2911, 0.0443, 0.0261, 0.0220, 0.0115, 0.0105, and 0.0067, respectively;

Based on the gray system theory, a multi-index gray relational analysis optimization model was established, and the development potentials of CBM blocks in complex geological conditions with interval values were ranked. The ranking results, from most to least optimal, are Block 2 (Sanjiao block), Block 1 (Fanzhuang-Zhengzhuang block), Block 4 (Daning-Jixian block), Block 3 (Gujiao block), and Block 5 (Fengrun block). The optimum membership degrees are 0.8936, 0.7500, 0.5123, 0.2808, and 0.1112, respectively. The results of the evaluation are in accordance with the actual conditions. The multi-index gray relational analysis optimization model with interval numbers for evaluation indices has practicability and can be used for quantitative evaluation and optimization of CBM blocks under complex conditions. This model is suitable for the CBM blocks in the range of 547 km²–675 km². When using this model, the index values must be representative and accurate.

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