Performance evaluation of bolter miner cutting head by using multicriteria decision-making approaches

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Received: 16 May 2017; Revised: 18 August 2017; Accepted: 8 November 2017

Abstract
A bolter miner is a new type of mining machinery with cutting and anchoring functions. Owing to its structural diversity, the cutting head performance of a bolter miner varies. However, there is still no effective method to evaluate the cutting head performance. Based on multi-aspect factors influencing the cutting head performance, the main factors such as the load fluctuation coefficient, mean torque, and specific energy were taken into account. Combined with the characteristics of multi-criteria decision-making approaches and the superiority of game theory in calculating the weight of the cutting performance indexes, an evaluation method based on the game-theory–extenics model is proposed. In addition, by combining the geological conditions of a particular coalmine, three pick layout schemes for the cutting head are compared, the final one of which was chosen through a performance evaluation. The results were successfully applied to the first shield bolter miner in China, and good results were obtained for engineering application.

Keywords : Extenics, Game theory, Bolter miner, Cutting head, Pick layout

1. Introduction

The traditional technology for coal lane tunneling is to cut in front using a cutting equipment and anchor at the back using a roof-bolter. The advancing speed of a cutting equipment is relatively quick, but the anchor work of a roof-bolter takes up too much time, leading to a serious imbalance in the excavation time. A bolter miner is a new type of mining machinery with cutting and anchoring functions, and can make the excavation and support stages progress synchronously, thereby improving the imbalance of the coal lane tunneling. The break up of coal-rock is completed using a front swingable cutting head. And the quality of its design directly affects the reliability, economy, and rapidity of the work being conducted. A cutting head is complex in structure and has a wide range of pick layouts, which have different geological adaptabilities. At the same time, how to select a cutting head with the best performance for the different working conditions has been widely studied by scholars both domestically and abroad (Jang et al., 2016; Kang et al., 2016; Zhang et al., 2016).

Differing from traditional cutting equipment, like a shearer or a roadheader, a bolter miner cutting head has no helical vane. And its difference in structure leads to a significant difference in mechanical properties between the cutting head and the helical drum (Ma, 2017; Gao et al., 2012). Owing to the short development time of a bolter miner (Vierhaus and Rainer, 2002; Leeming et al., 2001), there have been few reports on its pick layout of a cutting head thus far, however, many scholars have conducted in-depth studies on other helical drums used in cutting equipment. For example, the cutting torque, cutting force, and load fluctuation coefficient have been applied as indexes, and the best pick layout scheme of a shearer was selected under different working conditions (Zhao and He, 2011; Li et al., 2014; Du et al., 2009). Based on an analysis of the vertical vibration characteristics of a continuous miner (Li et al., 2010), it was pointed out that reducing
the drum load can effectively reduce the amount of vibration. The relationship between the blade wrap angle on a helical drum and the crushing effect was established, a forecasting formula for the cutting force was presented (Gunes et al., 2007).

In conclusion, as an object of research, there is an essential difference between a bolter miner and a traditional helical drum. At present, there are no studies on the pick layout of a cutting head, and thus improving the technology in this field is an urgent matter. From a research perspective, most scholars have paid greater attention to an analysis of the mechanical properties of mining machinery to obtain the best pick layout, and less on an analysis on the machinery performance. In this research, combined with the characteristics of multi-criteria decision-making approaches (Wang and Lin, 2013; Gauri and Chakraborty, 2009; Alireza et al., 2016; Yu et al., 2014; Kuniyuki et al., 2016) and the superiority of game theory (Sandru et al., 2013) in calculating the weight of the cutting performance indexes, a new evaluation method based on a game-theory–extenics model is proposed. Combined with the geological conditions of a certain coalmine, the cutting head performance is analyzed under different pick layouts, the results of which will provide a quantitative basis for a performance evaluation and preference decision-making of a cutting head.

2. Game-Theory–Extenics

The prediction of the cutting head performance is a complex task affected by many different factors required to evaluate such performance, as based on a weighted synthesis of multiple indexes. Owing to its creative decision-making skills, extenics has been highly recognized by the engineering community (Zhang et al., 2015; Yeh and Lin, 2016). However, extenics often determines the index weight through expert scoring, a linear function, entropy weight analysis, or other such methods. These approaches rely solely on the performance index weighting, and ignore their own attributes. Thus, the objective effect of each index on the cutting head performance needs to be considered based on the extenics. The accuracy of the performance can be ensured only when the objective and subjective weights are combined. In this study, game theory is introduced at the time of index weighting through which we can obtain the comprehensive subjective and objective weights and apply them to the cutting head performance evaluation. A flow chart of the classification forecasting of the performance using an improved matter-element extenics method is shown in Fig. 1.

Fig. 1 Flow chart of classification forecasting of performance using an improved matter-element extenics method

(1) Matter element model, classical field, sectional field

Matter element model. The matter element model for evaluating the cutting head performance can be expressed as follows:
where $R$ is the matter element, $N$ is the cutting head performance to be evaluated, $C$ is the characteristic for $N$, $C = \langle c_1, c_n \rangle$, and $X$ is the characteristic value, where $X = \langle x_1, x_n \rangle$.

**Classical field.** The classical field for all cutting head performance grades can be represented as follows:

\[
R_{0j} = \left( N_{0j}, C_j, X_{0ji} \right) = \left[ \begin{array}{c} N_{0j} \\ c_1 \ \ X_{0j1} \\
\vdots \\
\vdots \\
\vdots \\
\vdots \\
c_n \ \ X_{0jn} \end{array} \right] = \left[ \begin{array}{c} N_{0j} \\ \left\langle a_{0j1}, b_{0j1} \right\rangle \\
\vdots \\
\vdots \\
\vdots \\
\vdots \\
c_n \ \ \left\langle a_{0jn}, b_{0jn} \right\rangle \end{array} \right],
\]

where $N_{0j}$ is the cutting head performance ($j = 1, 2, m$), $C_i$ is the characteristic for the performance at $N_{0j}$ ($i = 1, 2, n$), and $X_{0ji}$ is the range of $C_i$ under the performance of $N_{0j}$.

**Sectional field.** The sectional field can be represented as follows:

\[
R_p = (P, C, X_p) = \left[ \begin{array}{c} P \\ c_1 \ \ X_{1p} \\
\vdots \\
\vdots \\
\vdots \\
\vdots \\
c_n \ \ X_{np} \end{array} \right] = \left[ \begin{array}{c} P \\ \left\langle a_{1p}, b_{1p} \right\rangle \\
\vdots \\
\vdots \\
\vdots \\
\vdots \\
c_n \ \ \left\langle a_{np}, b_{np} \right\rangle \end{array} \right],
\]

where $P$ represents the cutting head performance grade, $C$ is the characteristic for $P$, $C = \langle c_1, c_n \rangle$, $X_p$ is the characteristic value, and $X_p = \langle a_{1p}, b_{1p} \rangle$—$P$ is the range of values for the characteristic $c_n$, which is in $P$’s sectional field.

### (2) Initialization and standardization

For the cutting head performance indexes, the first step is the initialization. Because of the different dimensions among the cutting head performance indexes, the influence of each index dimension is not eliminated, and it is necessary to make the performance indexes dimensionless so that each index value is within the interval [0-1]. The standardization of the performance indexes is handled using a linear dimension method.

The larger, the better type:

\[
y = \frac{x - x_{\text{min}}}{x_{\text{max}} - x_{\text{min}}}. \tag{4}
\]

The smaller, the better type:

\[
y = \frac{x_{\text{max}} - x}{x_{\text{max}} - x_{\text{min}}}. \tag{5}
\]

where $y$ is the standardization value, $x$ is the index value, and $x_{\text{max}}$ and $x_{\text{min}}$ are the maximum and minimum values of each performance index.

### (3) Correlation degree function

According to the functional dependency of the matter-element model, the correlation degree of each performance index in terms of the pending decision and performance classification is given as
where $K_j(X_i(m))$ is the correlation degree of the $i$th performance index and performance $j$ for the cutting head performance in a pending decision, where $i$ is the performance index, $i = 1, 2, 3$; $j$ is the performance grade, $j = 1–7$; and $m$ represents the sample. The detailed meaning of each of these values is shown in Table 1.

| Parameter | Significance |
|-----------|--------------|
| $K_j(X_i(m)) \geq 1$ | The criterion in which the cutting performance index matches the performance grade $j$ |
| $0 \leq K_j(X_i(m)) < 1$ | The criterion in which the cutting performance index relatively matches the performance grade $j$ |
| $-1 < K_j(X_i(m)) < 0$ | The criterion in which the cutting performance index does not match the performance grade $j$ |

### (4) Index weighting

Aiming at obtaining the scientific and reasonable comprehensive weight of the performance indexes, it is necessary to adopt an appropriate method to integrate the subjective and objective weights. In this study, the game-theory–extenics method is combined with an expert scoring method and a linear function method. The details of these algorithms are as follows.

Using $L$ types of different methods to obtain the weight of the performance indexes ($L=2$), the weight of each index, and the weight vector $w_k=[w_{k1}, w_{k2}, \ldots, w_{km}]$, $(k=1, 2, \ldots, L)$, the linear combination of weight vectors $w_k$ is as follows:

$$ w = \sum_k^L \alpha_k w_k^\prime \quad (\alpha_k > 0), $$

where $w$ is a new weight vector, $\alpha_k$ is a linear combination coefficient, and $w_k^\prime$ is the original weight vector. $w_k^\prime$ is transport matrix of $w_k$.

Aiming to minimize the difference between the weight vectors $w$ and $w_k$ of the cutting head performance indexes and select the optimal weight value $w_k^*\prime$, the linear combination coefficients $\alpha_k$ are optimized through Eq. (10). From this, the countermeasure model is as follows:

$$ \min \sum_k^L \| \alpha_k w_k^\prime - w_k\|_2 \quad (k = 1, 2, \ldots, L). $$

Based on the differential properties of the matrices, it is not difficult to obtain the optimization in Eq. (11):
\[
\begin{bmatrix}
    w_{1} \cdot w'_{1} & w_{1} \cdot w'_{2} & \cdots & w_{1} \cdot w'_{L}
    \\
    w_{2} \cdot w'_{1} & w_{2} \cdot w'_{2} & \cdots & w_{2} \cdot w'_{L}
    \\
    \vdots & \vdots & \ddots & \vdots
    \\
    w_{L} \cdot w'_{1} & w_{L} \cdot w'_{2} & \cdots & w_{L} \cdot w'_{L}
\end{bmatrix}
\begin{bmatrix}
    \alpha_{1} \\
    \alpha_{2} \\
    \vdots \\
    \alpha_{L}
\end{bmatrix}
= \begin{bmatrix}
    w_{1} \cdot w'_{1} \\
    w_{2} \cdot w'_{2} \\
    \vdots \\
    w_{L} \cdot w'_{L}
\end{bmatrix}.
\]

MATLAB can be used to calculate the optimal value.

(5) Performance grade

The correlation degree of the performance is calculated using Eq. (12).

\[ K_{j}(N_{j}(m)) = \sum_{i=1}^{3} w_{ij}(m)K_{j}(X_{j}(m)), \]  
(12)

where \( K_{j}(N_{j}(m)) \) is correlation degree of the comprehensive performance, and \( w_{ij}(m) \) is the index weight.

When \( X_{j}(m) \not\in X_{0j}(\eta) \), it indicates that performance \( p \) is not within the given range, which needs to divide the performance newly.

When \( X_{j}(m) \in X_{0j}(\eta) \), calculate \( K_{j}(p) \), if

\[ K_{j\eta}(p) = \max K_{j}(p). \]  
(13)

This indicates that performance \( p \) belongs to the grade \( j_{0} \).

3. Engineering Design Application

3.1 Simulation Model of the Cutting Head

According to the geological conditions of Shendong Coalmine, where the coal quality belongs to easily crushed long flame coal and high-moisture non-caking coal, the rule of thumb is that preliminarily design 3 schemes of pick layout and make the performance evaluation and decision for the 3 schemes by the game-theory–extenics. The optimum pick layout scheme can then be selected. Pick layouts, divided into a single-sequence type, a double-checkerboard type, and a hybrid type, are shown in Fig. 2. The total number of transversal lines is 12, and the transversal distance is 0.075 m.

![Fig. 2 Different pick layouts of cutting head](image)

(a) Single-sequence type  
(b) Double-checkerboard type  
(c) Hybrid type

In this study, a main strain failure and a shear strain failure are used to accurately reflect the damage failure of coal-rock (Zhu and Li, 2015; Xu et al., 2013). When the principal or shear strain of the coal-rock model unit reaches the set value, some elements of the coal-rock will disappear automatically. And the coal-rock material parameters in Shendong
Coalmine were obtained by mechanical experiments, the uniaxial compressive strength of coal-rock is 15 MPa. The detailed parameters of which are shown in Table 2.

| Parameter                                      | Value |
|------------------------------------------------|-------|
| Angle of internal friction / °                 | 52    |
| Friction coefficient between pick and coal-rock| 0.15  |
| Friction angle between pick and coal-rock / °  | 8.53  |
| Uniaxial compressive strength / MPa            | 15    |
| Shear strength / MPa                           | 1.4   |
| Tensile strength / MPa                         | 0.6   |

During the simulation, the bottom of the coal-rock is fixed, and unconditional reflection boundary conditions are applied to simulate the real conditions of an infinite extinction of coal-rock. In addition, the movement of the bolter miner cutting head is synthesized through feed motion and rotation along the centerline of the roller, and the crushing of the coal-rock is accomplished through the rotation of different numbers of conical picks. The cutting coal-rock model of the cutting head is shown in Fig. 3.

![Fig. 3 Cutting coal-rock model of cutting head](image)

### 3.2 Classification standard

The cutting head performance is influenced by many factors. Referring to research by many scholars on helical drum performance indexes, the following three indexes were selected in this paper to evaluate the cutting head performance.

1. **Specific energy, \( SE \)**: This reflects the energy consumption when the cutting head cuts the unit volume of coal-rock, and is the key economic index for a bolter miner. The larger the value is, the greater the energy consumption and the lower the cutting efficiency. This is not only related to the physical properties of the coal-rock, but also to the pick configuration parameter and the cutting head movement parameter. The model of specific energy is

   \[
   SE = \frac{\bar{w}_j L \rho}{M},
   \]  

   where \( \bar{w}_j \) is the mean cutting force (kN), \( L \) is the cutting length (mm), \( \rho \) is the density of the coal-rock, and \( M \) is the weight of the coal-rock (g).

2. **Mean torque, \( T \)**: This reflects an important characteristic of the cutting load, that is, the higher the mean value, the higher the load. There is a direct relationship among the strength of the coal-rock, the pick configuration, and pick layout parameters.

   \[
   \bar{T} = \left( \sum_{k=1}^{n} T_k \right) / n,
   \]  

   where \( n \) is the total number of data acquisitions, and \( T \) is the cutting torque.

3. **Load fluctuation coefficient, \( \sigma \)**: This reflects the degree of load fluctuation of the cutting head. The number of conical picks and the state of stress during cutting can change at any moment. Therefore, the load of the cutting head...
fluctuates within a circle. The load fluctuation coefficient indicates the degree of fluctuation of the cutting force, which is an important indicator measuring the reliability of the cutting head. The larger the value is, the stronger the load fluctuation. The model of the load fluctuation evaluation index is

$$\delta_j = \frac{1}{\bar{w}_j} \sqrt{\frac{1}{N} \sum_{j=1}^{N} (w_j - \bar{w})^2},$$

(16)

where $w_j$ is the cutting force, $\bar{w}_j$ is the mean cutting force, and $N$ is the sampling point for the cutting head.

### Table 3 Criteria of dimensionless indices with performance grade

| Grade | $\delta_j$ | $\bar{T}$ / (N-m) | $SE$ / (kW-h/m$^3$) |
|-------|-----------|-----------------|-----------------|
| I     | 0.360     | 0.440           | 0.680           |
| II    | 0.360-0.400 | 0.440-0.470    | 0.680-0.720     |
| III   | 0.400-0.440 | 0.470-0.500    | 0.720-0.760     |
| IV    | 0.440-0.480 | 0.500-0.530    | 0.760-0.800     |
| V     | 0.480-0.520 | 0.530-0.560    | 0.800-0.840     |
| VI    | 0.520-0.560 | 0.560-0.590    | 0.840-0.880     |
| VII   | 0.560-1     | 0.590-1        | 0.880-1         |

The matter-element evaluation model is based on the cutting head performance indexes, which are required to first determine the distribution range of each index value under a different pick layout, and provide the basis for the subsequent correlation calculation degree. Through the above three indexes, combined with relevant studies regarding the shearer, roadheader, and other mining machinery, the cutting head performance is divided into seven grades, which are extremely strong (I), stronger (II), strong (III), medium (IV), poor (V), bad (VI), and extremely bad (VII). The classification standards for the cutting head performance are shown in Table 3.

As shown in Table 4, three sets of actual data are obtained, and dimensionless is carried out for each performance index.

### Table 4 Index values for different pick layout schemes

| Number | Pick layout            | $\delta_j$ | $\bar{T}$ / (N-m) | $SE$ / (kW-h/m$^3$) |
|--------|------------------------|-----------|-----------------|-----------------|
| 1      | Single-sequence type   | 0.359     | 23830(0.433)    | 2.392(0.683)    |
| 2      | Double-checkerboard type | 0.367    | 32671(0.594)    | 2.845(0.813)    |
| 3      | Hybrid type            | 0.368     | 22060(0.401)    | 2.350(0.671)    |

### 3.3 Cutting Head Performance Evaluation

#### (1) Determination of matter element

Based on extenics, the cutting head performance indexes of a single-sequence type are selected to ensure the matter-element of the cutting head performance. The matter-element evaluation model is

$$R = \begin{pmatrix} p, & 0.683 \\ c_1, & 0.433 \\ c_2, & 0.359 \end{pmatrix}.$$

#### (2) Correlation calculation.

The correlation degree of the cutting head for each performance parameter and performance grade is calculated using Eq. (6). The results are shown in Table 5.
(3) Game theory classified index weighting
Considering that the degree of importance of the specific energy is slightly lower than the other indexes in engineering practice, the subjective weight of the performance indexes is obtained through an expert scoring method (Hou, 2016), where the fluctuation coefficient is 0.4, the mean torque is 0.4, and the specific energy is 0.2. As shown in Table 6, the objective weights of the performance indexes are obtained using a linear function method. Based on game theory, the two kinds of weights are mixed together through Eq. (9), and the comprehensive weights of the indexes are as shown in Table 6.

Table 6 Objective-dynamic and synthetic weight values of eigenvalue

| Parameter          | $\delta_j$ | $\bar{T}$ | $SE$ |
|--------------------|------------|------------|------|
| Objective weight   | 0.300      | 0.330      | 0.370|
| Comprehensive weight | 0.347     | 0.363      | 0.290|

(4) Performance evaluation
The degree of correlation between the cutting head and performance at all grades is calculated using Eq. (13). The associated values are as shown in Table 7.

Table 7 Degree of correlation in assessed performance

| Correlation | $K_1 (p)$ | $K_2 (p)$ | $K_3 (p)$ | $K_4 (p)$ | $K_5 (p)$ | $K_6 (p)$ | $K_7 (p)$ |
|-------------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| Results     | 0.003     | -0.018    | -0.094    | -0.169    | -0.232    | -0.286    | -0.332    |

Compared with the calculation results of each correlation degree,

$$K_{ij} (p) = \max K_j (p) = 0.003$$

It was concluded that the cutting head performance of a single-sequence type is extremely strong under the condition considered. Through the above method, the correlation degree of each performance index and the performance evaluation grade of the other cutting heads were calculated, the results of which are shown in Table 8 and Fig. 4.

According to Table 8 and Fig. 4, the cutting head performance of single-sequence type under the current conditions is better than that of a double-checkerboard type and a hybrid type. The ranking of the cutting head performance is as follows: single-sequence type > hybrid type > double-checkerboard type. These results show the virtues and defects of the three cutting heads. It can be concluded that a single-sequence type should be applied to practical engineering based on a comprehensive consideration.

Table 8 Performance evaluation results

| Type             | $K_1 (p)$ | $K_2 (p)$ | $K_3 (p)$ | $K_4 (p)$ | $K_5 (p)$ | $K_6 (p)$ | $K_7 (p)$ | results |
|------------------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|---------|
| Single-sequence  | 0.003     | -0.018    | -0.094    | -0.169    | -0.232    | -0.286    | -0.332    | I       |
| Double-checkerboard | -0.255   | -0.158    | -0.171    | -0.119    | 0.020     | -0.127    | -0.181    | V       |
| Hybrid           | 0.029     | 0.035     | -0.117    | -0.189    | -0.249    | -0.301    | -0.346    | II      |
(5) Application results

The cutting head was designed as a single-sequence type. It adopts a scalable drum structure, consisting of four single-sequence type drums. As shown in Fig. 5, the cross-section of the cutting head is a standard rectangle. At present, the bolter miner has been operating in the Shendong Coalmine. During the tunneling process, the cutting head using a 1 m cycle, the advancing speed can be adjusted for the whole load, and the actual operating speed of the machinery does not exceed 8 m/min. The monthly advancement reaches 3,600 m. The machinery operates well, and its crushing capability is good. The results indicate that the improved matter-element model based on extenics and game theory can effectively predict the cutting head performance, and provides a quantitative basis for a performance evaluation and prediction.

4. Conclusion

In this study, the factors affecting the cutting performance were considered, such as the load fluctuation coefficient, mean torque, and specific energy consumption. Through the use of extenics, the weights from an expert scoring method were integrated with those a simple correlation function method, and a comprehensive weight was obtained. Based on the geological conditions of the Shendong Coalmine, game-theory–extenics was used to evaluate the performances of three different types of cutting head, and the best pick layout scheme was obtained.

The results of this study have been successfully applied to the development of the first shield-type bolter miner in the world. The reliability of the game-theory–extenics was verified based on a trial operation, the results of which have provided a new method for a performance evaluation and prediction determination of a bolter miner cutting head.

Acknowledgment
This research was supported by the Strategic Emerging Industry Technology Research Program of Hunan (2015GK1009), and the Fundamental Research Funds for the Central Universities of Central South University (2017zzts094).

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