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Study on the evaluation index system and evaluation method for self-elevating drilling unit design

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Abstract: In the process of designing self-elevating drilling unit, it is important, yet complicated, to use comparison and filtering to select the optimum scheme from the feasible ones. In this research, an index system and methodology for the evaluation of self-elevating drilling unit was proposed. Based on this, a multi-objective combinatorial optimization model was developed, using the improved grey relation Analysis (GRA), in which the analytic hierarchy process (AHP) was used to determine the weights of the evaluating indices. It considered the connections within the indices, reflecting the objective nature of things, and also considered the subjective interests of ship owners and the needs of designers. The evaluation index system and evaluation method can be used in the selection of an optimal scheme and advanced assessment. A case study shows the index system and evaluation method are scientific, reasonable, and easy to put into practice. At the same time, such an evaluation index system and evaluation method will be helpful for making decisions for other mobile platforms.

Keywords: self-elevating drilling unit; evaluation index system; evaluation method; grey relation analysis (GRA); analytic hierarchy process (AHP)

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1 Introduction

With the development of worldwide exploitation for ocean resources, offshore platforms are playing a dominant role in the oil and gas industry for exploration and production of natural resources, which have been designed to operate at various locations with different sea-bed conditions, great water depths and under various sea conditions[1-2]. Self-elevating drilling unit which was invented in 1950 and used for exploration and extraction of hydrocarbons from the ocean beds is a main structural type of mobile platforms, and it accounts for about 65% of the mobile platform market.

The concept design of self-elevating drilling unit is an important stage because on the first hand, it determines the overall quality of the platform system, on the other hand, the major opportunities for cost savings occur in this optimization process, and approximately 70% of the life-cycle costs are frozen in the end of this stage[3-4]. At the same time, the concept design must synthesize these elements of technical factors, economic factors, market demands, ship-owner's requirement, etc., so how to evaluate the provided feasible schemes of concept design is a multi-objective decision-making problem[5]. The optimization of self-elevating drilling unit is a key point of concept design and a primary factor concerning investment. It is necessary to select the best from feasible schemes through comparison and filter. Generally, optimization is complex in practical operation as it involves multiple, usually conflicting indices, which consist of many qualitative and quantitative factors of uncertainty and fuzziness. The main problem is to establish suitable evaluation index system and choose the evaluation method, but the research and work are very limited in it. The evaluation index system and evaluation method for the concept design of self-elevating drilling unit are proposed in this paper based on the research of self-elevating drilling unit in recent years and the suggestions of experts.

2 The establishment of evaluation index system for self-elevating drilling unit

Establishing the evaluation index system[6] is crucial for the evaluation. The index system comprises several individual evaluation indexes, which can reflect various requirements of the question. The principle of establishing index system is practical, entire, reasonable, scientific, and mainly acceptable for relevant personnel and branches. The design of self-elevating drilling unit is a process of design-evaluation-redesign forming a spiral circular ascending course. The process is very

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complicated due to many factors such as multi-objective, diversity of solutions, complexity of redesign correlation of variants, diversity and fuzziness of knowledge, and so on.

The influencing factors for the working environments and functions of the self-elevating drilling unit are various during the design. It includes the main dimensions, general arrangement, capacity of cabins, water depth, maximum drilling depth, variable deck load, cantilever load, rig load, power equipments, lifting system, rig ability, design load, towing stability, intact stability, damage stability, standing stability, anti-slide performance, hydrostatic ability, control ability, environmental protection performance safety level, and so on. When evaluating the design scheme of the self-elevating drilling unit, there is no need to think over all kinds of the previous aspects. It isn't feasible. In the light of the principle of building the evaluation index system, the types and the quantity of evaluation indices must be clear. Each index is independent and not overlapping. Choose the chief factors to influence the performance and grasp the main contradictions. After full-scale analytical discussions, it is considered that the major factor affecting the self-elevating drilling unit's working functions and technical level includes light weight, rig ability, hook loading, variable deck load, main engine power, cantilever movement scope, water depth, and so on. At the same time, the cantilever movement scope and water depth should be given in the design program. Based on previous analysis, the survey of the study and design for the self-elevating drilling unit and considering the suggestions from experts, this paper presents an evaluation index system to optimize feasible scheme, and the index system comprises five indexes:

1) Drilling depth coefficient (R_{D_d}): this index is the benefit type, which embodies the drilling ability of the self-elevating drilling unit under the same light weight. As index value becomes bigger, it is beneficial to the ship-owner, and the unit of this index is m/t.

$$R_{D_d} = \frac{D_d}{W_L} .$$

D_d is drilling depth, the maximum drilling depth for the self-elevating drilling unit, and its unit is meter. W_L is light weight, including the weight of hull, machineries, drilling equipments, and so on, excluding the weight of oil water, spare parts and suppliers, and its unit is ton.

2) Water depth coefficient (R_{D_w}): generally, the standing stability of the self-elevating drilling unit requires larger model length with deeper water depth. Smaller model length under the same water depth is expected. The bigger the coefficient, the better the design. It belongs to benefit index.

$$R_{D_w} = \frac{D_w}{l} .$$

D_w is water depth, the maximum water depth for the self-elevating drilling unit, and its unit is meter. l is the model length of platform, and its unit is meter.

3) Variable deck load coefficient (R_F): the index embodies the ability to endure the variable deck load of the self-elevating drilling unit under the same light weight and the ability of self maintaining. The index belongs to benefit indices. For its value, bigger is always better.

$$R_F = \frac{F}{W_L} .$$

F is variable deck load, the maximum variable deck load for the self-elevating drilling unit, and its unit is ton.

4) Ratio price to performance coefficient (R_p): the index embodies economy performance of the self-elevating drilling unit under the same water depth. This index belongs to cost indices and its unit is ten thousand-yuan/m. For its value, smaller is always better.

$$R_p = \frac{p}{D_w} .$$

p is price, the whole investment of building the platform, including the design fee, construction cost, equipment purchases fee and other cost, the unit is ten thousand yuan.

5) Oil consumption per unit drilling depth coefficient (R_Q): the index embodies the oil consumption of platform under the same unit drilling depth. This index belongs to cost indices and its unit is t/m. For its value, smaller is always better.

$$R_Q = \frac{Q}{D_a} .$$

Q is daily oil consumption, the amount of oil consumption per day for the self-elevating drilling unit, including fuel oil and lubricating oil, and its unit is ton. D_a is daily advance, the amount of drilling depth per day for the self-elevating drilling unit, and its unit is meter.

3 The multi-objective combinatorial optimization model based on Advanced GRA

3.1 Methodology

3.1.1 Concepts of grey relation analysis

Grey system theory was formulated by Ju-long Deng in 1982[7]. According to this theory, it is called a white system if its internal information is completely known, such as architecture, operation mechanism, system characteristics and parameters, etc. On the contrary, a system is defined as a black system if no information and characteristics about the system can be known. Grey space is thus defined as a system between the white and black systems. That is, the information and messages of the grey system are partially clear, but the others are not. Grey system theory is to study the problem of grey space about its analysis, modelling, forecasting, decision-making and controlling. Compared with traditional regression statistical methods which require more data and time, the grey system needs minimal data to get reasonable and good results. By now, the grey system has been applied in many fields, such as economics, agriculture, geography, weather, earthquakes, science, etc[8].

The grey relation analysis (GRA) is an important part of the grey system theory, and the mathematics of GRA derives from space theory (Deng, 1988). The purpose of grey relational analysis is to measure the relative influence of the compared series on the reference series. In other words, the calculation of GRA reveals the relationship between two discrete series in a grey space. The degree of influence of a compared series on the reference series, the grey relational grade (GRG), can be represented by the relative distance between them in an imaging grey space without making prior assumption about the distribution type. The smaller the distance, the larger the influence. The key problem is to calculate the GRG during GRA.

Let $X=\{x_\sigma = | \sigma = 0,1,2,\cdots,m\}$ be a given grey relation factor set, $x_0 \in X$ be the series of the reference factor, and $x_i \in X (i \neq 0)$ be the series of the compared factors; $x_0(k)$ and $x_i(k)$ are the values of x_0 and x_i at time k, respectively. The grey relational grade γ_{0i} between x_i and x_0 must then satisfy the following four relational axioms in space theory[9].

1) Space norm interval:

$0 < \gamma[x_0(k),\ x_i(k)] \leq 1$,

$x_0(k) \in x_0 \in X,\ x_i(k) \in x_i \in X$,

$\gamma[x_0(k),\ x_i(k)]=1$, iff $x_0(k) = x_i(k)$,

$\gamma[x_0(k),\ x_i(k)]=0$, iff $x_0 \in \varphi, x_i \in \varphi, X \in \varphi$.

2) Space duality symmetric:

$\gamma[x_0(k),\ x_i(k)] = \gamma[x_i(k),\ x_0(k)]$, iff $X=\{x_0, x_i\}$.

3) Space wholeness:

$\gamma[x_i(k),\ x_j(k)] \neq \gamma[x_j(k),\ x_i(k)]$ (almost always), $x_i(k), x_j(k) \in X$.

4) Space approachability:

$\gamma[x_0(k),\ x_i(k)]$ increases as the distance Δk decreases. $\Delta k = |x_i(k) - x_0(k)|$.

GRG represents the degree whereby two factors can be related. It describes the relative variations between two factors indicating magnitude and gradient in a given system. If the relative variations of two variables are basically consumed consistent in the development trend, then the GRG between these two variables is large[10].

The GRG between two series at a certain time point is called relational coefficient $\xi_{i0}(k)$, which is also called 'point' relational grade. Before calculating grey relational coefficients, grey data processing is often necessary. Series with various units need to be transformed to have the same numeric order. Usually, each series is normalized by dividing respective data of the original series by their averages $x_i^{'}(k) = \dfrac{x_i(k) - x_{\min}(k)}{x_{\max}(k) - x_{\min}(k)}$, or using the method of effect measure transfer which is for the benefit index $x_i^{'}(k) = \dfrac{x_i(k)}{x_{\max}(k)}$, and for the cost index $x_i^{'}(k) = \dfrac{x_{\min}(k)}{x_i(k)}$. After performing grey data processing, let the transformed reference series be $x_0=\{x_0(1), x_0(2),\cdots, x_0(n)\}$, then the m compared series are denoted by $x_i=\{x_i(1), x_i(2),\cdots, x_i(n)\}$, i=1 to m. The relational coefficient $\xi_{i0}(k)$ between the reference series $x_0(t)$ and the compared series $x_i(t)$ at time $t=k$ can be calculated by the following equation, which satisfies the four relational axioms mentioned above, which represents the relative distance between two factors.

$$\xi_{0i}(k) = \frac{\min\limits_i \min\limits_k |x_0(k) - x_i(k)| + \rho \max\limits_i \max\limits_k |x_0(k) - x_i(k)|}{|x_0(k) - x_i(k)| + \rho \max\limits_i \max\limits_k |x_0(k) - x_i(k)|} = \frac{\Delta(\min) + \rho\Delta(\max)}{\Delta_{0i}(k) + \rho\Delta(\max)}, \tag{1}$$

where $|x_0(k) - x_i(k)|$ denotes the absolute difference between the two series, representing the distance $\Delta_{0i}(k)$ after data transformation. Besides,

$$\Delta(\min) = \min_i \min_k |x_0(k) - x_i(k)|, \text{ and}$$

$$\Delta(\max) = \max_i \max_k |x_0(k) - x_i(k)|$$

are the minimum distance and maximum distance for all time in all compared series, which form a comparison environment. Usually, $\Delta(\min)$ equals zero since the transformed series will intersect at a certain point. ρ ($0<\rho<1$) is a distinguishing coefficient used to adjust the range of the comparison environment, and to control level of the relation coefficients. When $\rho=1$, the comparison environment is unaltered; when $\rho=0$, the comparison environment disappears. Usually, ρ is taken as 0.5 to perform the GRA because this value offers moderate distinguishing effects and good stability.

Assume that every point in a series has equal importance, then the GRG, i.e. 'line' relational grade or 'series' relational grade, can be obtained by averaging reconditions coefficients at all time points:

$$\gamma_{0i} = \frac{1}{n}\sum_{k=1}^{n}\xi_{0i}(k) \ . \tag{2}$$

The aim of GRA is to recognize the geometric relationship between two sets of time series data in relational space. If the data of the two series at all respective time points are the same, then the relational coefficients all equal one, the same as the relational grade. On the other hand, since it is impossible for any two transformed series to be perpendicular to each other, the grey relational coefficients are greater than zero, the same as the relational grade. Larger GRG means that the tendency variation of compared series is more consistent with the reference series.

3.1.2 Analytic hierarchy process (AHP)

The analytic hierarchy process (AHP) was first introduced by Saaty in 1971 to solve the scarce resources allocation and military planning[11]. Since its introduction, the AHP has become one of the most widely used multi-objective decision-making methods, and has been used to solve unstructured problems in different areas of human needs and interests, such as politics, economy, society and management sciences. The procedures of the AHP involve six essential steps [12-13].

1) Define the unstructured problem and state clearly the objectives and outcomes.

2) Decompose the complex problem into a hierarchical structure with decision elements (criteria, detailed criteria and alternatives).

3) Employ pairwise comparisons among decision elements and form comparison matrices.

4) Use the eigenvalue method to estimate the relative weights of the decision elements.

5) Check the consistency property of matrices to ensure that the judgments of decision makers are consistent.

6) Aggregate the relative weights of decision elements to obtain an overall rating for the alternatives

3.2 Multi-objective combinatorial optimization model for self-elevating drilling unit

The purpose of GRA is to explore the qualitative and quantitative relationships among abstract and complex series and to capture their dynamic characteristics during the development process[14-15].

GRA analyses the similarity of curve's geometric shape of the compared series to the reference series and draws the conclusion based on the calculation of the GRG: the larger the value of GRG, the more similar it is. As for the multi-objective decision-making problems, weight is one of the primary components and a significant parameter to express designers' knowledge experience and judgment preference[4], usually, GRA does not consider the weight vector. In this paper, the multi-objective combinatorial optimization model is established for the concept design of self-elevating drilling unit. In the model, the evaluation indices of each feasible scheme for the concept design of self-elevating drilling unit are chosen as the compared series and the evaluation indices of the ideal scheme as the reference series, the value of GRG reflects the approaching degree of the feasible schemes to the ideal scheme. The method of AHP is used to calculate the weights of the indices in GRA, using the average of the product of weight vector and indices relational coefficient matrix as GRG. In this way, the optimization model can reflect the correlation of the indices in the evaluation index system to some extent, considering the ship-owner's preference, designers' knowledge experience, market demands, and so on. Fig.1 is the hierarchical structure of improved GRA, when the weights of the indices get different values, the sequence of the compared series to reference series will change.

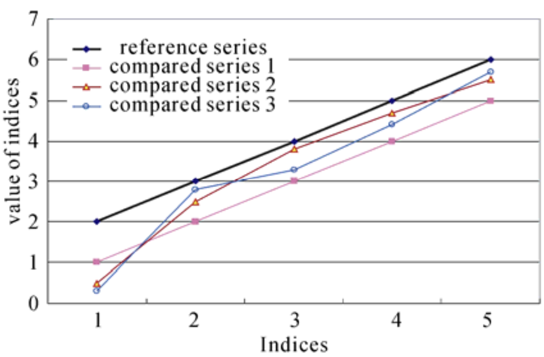

Fig.1 Hierarchical structure of improved GRA

Based on the previous analysis, after performing grey data processing, let X={ x_σ =| σ =0,1,2, ⋯, m} be a given grey relation factor set composed of the indices in the evaluation index system, $x_i \in X(i \neq 0)$ be the series of the compared factors composed of the indices of feasible schemes, and $x_0 \in X$ be the series of the reference factors composed of the indices of the ideal scheme; $x_i(k)$ donates the value of the kth evaluation index in the ith feasible scheme, $x_0(k)$ donates the value of the kth evaluation index in the ideal scheme, the value of the $x_0(k)$ is

$$x_0(k)=\max\{x_i(k)\}, \tag{3}$$

where i=1, 2,⋯, m. The relational coefficient $\xi_{0i}(k)$ between the reference series $x_0(k)$ and the compared series $x_i(k)$ can be calculated by Eq.(1), and the grey relational grade γ_{0i} between x_i and x_0, can be obtained by the fowling equation:

$$\gamma_{0i}=\frac{1}{n}\sum_{k=1}^{n}\omega_k\xi_{0i}(k), \tag{4}$$

where i=1,2,⋯,m; ω_k is the index weight vector which is calculated by the method of AHP. Larger γ_{0i} means the feasible scheme x_i more tends to the ideal scheme x_0. The objective factors of the decision schemes and the subjective factors of the decision-makers have been systematically considered in this mode.

4 Case study

To demonstrate the effectiveness of the evaluation index system and the multi-objective combinatorial optimization model for the concept design of self-elevating drilling unit, four feasible schemes of the self-elevating drilling unit designed by Dalian University of Technology for Liaohe Petroleum Exploration Bureau[15] were chosen in this study. The maximum working water depth D_w is 35 m and the maximum drilling depth D_d is 6 000 m in this design, and the evaluation indices are shown in Table 1.

Table 1 The evaluation indices of the feasible schemes

Feasible schemes	R_{D_d} /(m/t)	R_{D_w}	R_F	R_P/(10000 ￥/m)	R_Q /(t/m)
1	1.239 4	0.583 3	0.313 4	0.074 3	12.117 6
2	1.303 2	0.833 3	0.304 1	0.068 6	11.404 8
3	1.250 0	0.648 1	0.291 7	0.065 7	11.547 4
4	1.309 2	0.711 4	0.305 5	0.062 9	11.689 9

Before calculating grey relational coefficients, grey data processing is often necessary. Series with various units need to be transformed to have the same numeric order. Each series is normalized by the method of effect measure transfer. The results of data processing are presented in Table 2.

Table 2 The evaluation indices of the feasible schemes

Feasible schemes	R_{D_d} /(m/t)	R_{D_w}	R_F	R_P/(ten thousand yuan/m)	R_Q/(t/m)
1	0.946 7	0.700 0	1.000 0	0.846 6	0.941 2
2	0.995 4	1.000 0	0.970 3	0.916 9	1.000 0
3	0.954 8	0.777 8	0.930 8	0.957 4	0.987 7
4	1.000 0	0.853 7	0.974 8	1.000 0	0.975 6

Construct the ideal scheme according to the values of Table 2 and Eq.(3): $x_0(1)$=1, $x_0(2)$=1, $x_0(3)$=1, $x_0(3)$=1, $x_0(4)$=1, $x_0(5)$=1, that is, x_0= {1, 1, 1, 1, 1}. Combining with $\Delta_{0i}(k)=|x_0(k)-x_i(k)|$ can derive the absolute difference matrix:

$$\begin{bmatrix} 0.053\,3 & 0.300\,0 & 0.000\,0 & 0.153\,4 & 0.058\,8 \\ 0.004\,6 & 0.000\,0 & 0.029\,7 & 0.083\,1 & 0.000\,0 \\ 0.045\,2 & 0.222\,2 & 0.069\,2 & 0.042\,6 & 0.012\,3 \\ 0.000\,0 & 0.146\,3 & 0.025\,2 & 0.000\,0 & 0.024\,4 \end{bmatrix},$$

where $\Delta(\max)$ =0.3 and $\Delta(\min)$ =0. Combining with equation (1) can derive the indices relational coefficient matrix:

$$\begin{bmatrix} 0.737\,8 & 0.333\,3 & 1.000\,0 & 0.494\,3 & 0.718\,3 \\ 0.970\,4 & 1.000\,0 & 0.834\,8 & 0.643\,5 & 1.000\,0 \\ 0.768\,4 & 0.403\,0 & 0.684\,2 & 0.778\,7 & 0.923\,9 \\ 1.000\,0 & 0.506\,3 & 0.856\,1 & 1.000\,0 & 0.860\,1 \end{bmatrix},$$

where ρ =0.5. According to each index's relatively important degree, the methods of AHP and 1 to 9 comparing scale are used to construct the judging matrix $\boldsymbol{A}$, at the same time, the weight vector of the five indices can be got, and the consistency of the judging matrix is verified:

$$\boldsymbol{A}=\begin{bmatrix} 1 & 5 & 1/4 & 1 & 1 \\ 1/5 & 1 & 1/7 & 1/5 & 1/5 \\ 4 & 7 & 1 & 4 & 4 \\ 1 & 5 & 1/4 & 1 & 1 \\ 1 & 5 & 1/4 & 1 & 1 \end{bmatrix} \quad \boldsymbol{\omega}=\begin{bmatrix} 0.1532 \\ 0.0405 \\ 0.4999 \\ 0.1532 \\ 0.1532 \end{bmatrix}.$$

$\lambda_{\max}$=5.1379; CI=0.034 5; RI=1.12; M=0.030 8

there coincidence rate M<0.1, therefore judging matrix $\boldsymbol{A}$ has satisfactory coincidence. Combining with Eq.(4) can derive the GRG of the four feasible schemes, which are presented in Table 3.

Table 3 GRG of the four feasible schemes

Feasible schemes	Scheme1	Scheme2	Scheme3	Scheme4
GRG	0.812 2	0.858 3	0.736 9	0.886 7

The calculation results show that scheme 4 is an optimal one in the four feasible schemes about the combined properties, and the result is consistent with the practical selection. By the case study, the application of the evaluation index system and the multi-objective combinatorial optimization model to the concept design of self-elevating drilling unit is described.

5 Conclusion

In recent years, the self-elevating drilling unit has been more extensively designed and built, the feasible schemes' evaluation and selection for the concept design of self-elevating drilling unit are important and complicated, but the research and work are very limited in the area. In this paper, the evaluation index system and the multi-objective combinatorial optimization model are established for the concept design of self-elevating drilling unit. In this way, the optimization model can reflect the correlation of the indices in the evaluation index system to some extent, considering the objective factors of the decision schemes and the subjective factors of the decision-makers. A case study demonstrates the feasibility of the proposed framework and methodology. The result from the study not only confirms the evaluation index system to be scientific, reasonable and simple, but also proves the utility of the multi-objective combinatorial optimization model. In addition, the evaluation index system will be helpful to evaluating the feasible schemes of the other kind mobile platform, and the multi-objective combinatorial optimization model can be used to solve some other multi-objective decision-making problems.

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自升式钻井平台方案评价指标体系及评价方法研究

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摘　要：本文对自升式钻井平台的方案评价指标体系和评价方法进行了研究，提出了一套适用于自升式钻井平台的方案评价指标体系，并采用改进的灰关联分析法进行平台方案的优选，初步分析和计算实例表明，该评价指标体系和评价方法是适用和可靠的. 通过对联分析方法进行改进，建立了适用于自升式钻井平台方案选优的灰关联多目标综合评价模型，该模型在灰关联分析的基础上引进层次分析法计算各指标的权重值，既在一定程度上考虑了设计方案各指标间的关联性，反应了事物的客观本质，又能体现船东的主观偏好和设计者的设计需要. 同时该方案评价指标体系和评价方法具有拓展性，可应用于其它类型的移动式平台，作为方案选择时的参考依据.

关键词：自升式钻井平台；评价指标体系；评价方法；灰关联分析；层次分析