Eco-econo-efficiency Based Quota Allocation towards Coal De-capacity Reform Implementation: Case Study from China

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Abstract. Reducing coal capacity is an essential part of China’s energy transition, with the formulation of a coal de-capacity quota allocation plan the key to achieving its coal overcapacity reductions. This paper presents a coal de-capacity quota allocation mechanism based on a comprehensive consideration of the ecological, economic, and efficiency concerns at the enterprise level to deal with China’s coal overcapacity problems. A multi-objective optimization quota allocation model based on equilibrium strategy is established for the decision makers, in which the ecological concerns are measured by three waste emissions, the economic concern assessed based on the coal de-capacity costs, and the efficiency measured using a DEA method. By introducing a membership function method, the model is transformed into its equivalent single form and solved using LINGO software. To prove the practicality of the model, a case analysis was conducted. The results indicate that due to the different ecological and economic level in each coal mine, the allocation ratio of each coal mine for coal de-capacity is quite different. Compared with the government plan to reduce overcapacity in the mining area, the ecological benefits of the enterprise’s strategy increases by 4.69 million tonnes, and the economic costs has reduced 42.79 million CNY. A sensitivity analysis under different parameters for the decision maker preferences implemented, and the production efficiency changes in the mining areas analyzed and compared. It was found that although coal capacity reduction quota allocations can be affected by the decision makers preferences, the comprehensive ecological, economic, and efficiency objectives at small scale, low-efficiency coal mines should take on additional coal capacity reduction tasks. After the optimal allocations, the efficiencies in all mining areas reached an optimal value. Keywords: Coal de-capacity, Quota allocation, Eco-econo-efficiency equilibrium, Multiobjective optimization.

1 Introduction

As a developing country experiencing rapid economic growth, China has a huge energy demand [1], with coal still being an important part of China’s energy structure [2]. Since 2000, China’s coal industry has developed rapidly [3]. The National Bureau of Statistics reported that from 2001 to 2013, China’s coal industry fixed asset investment increased by 16 times [4]. However, from 2014, a new trend has emerged in China’s coal production and supply

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As China enters a post-industrial stage, its dependence on coal for economic growth has begun to decline, with its coal production now lower than its coal production capacity. Therefore, China’s coal industry oversupply is becoming more obvious, and the coal overcapacity problems becoming more serious. Coal overcapacity has resulted in a series of problems, such as sharp declines in enterprises’ profits, serious waste of resources, and serious environmental pollution, which in turn has affected industry development and environmental governance. Therefore, solving the problem of coal overcapacity has become the key to China’s sustainable energy development.

Traditional approach to addressing overcapacity relying on the free market, mainstream economics believes that the free market makes inefficient manufacturers leave automatically. However, such a self-adjustment process usually full of obstacles, including the high cost of personnel placement and asset disposal, political influences opposed to shut downs, which may takes a long time and bring huge costs. Therefore, in recent years, Chinese government has been relying on powerful measures to curb overcapacity. Through the joint efforts of all regions, the total de-capacity task was completed ahead of schedule, which reflects the importance of addressing overcapacity through administrative measures.

Although administrative measures have a positive effect on overcapacity, however, in reality, due to the personnel placement, asset disposal, and debt problems brought about by the de-capacity process, the de-capacity policy has not been well implemented at the enterprise level. Many enterprises, including large state-owned enterprises, have only accomplished the task of de-capacity through superficial means. For example, in 2017, the National Development and Reform Commission issued the “Preliminary Opinions on Reducing Excess Production Capacity and Realizing the Development of the Iron and Steel and Coal Industries” Report, which pointed out that during the “13th Five-Year Plan” period, coal enterprises in large coal-producing areas must close coal mines with annual production capacity of less than 60 million tons. However, according to a survey by the National Energy Administration, many coal groups have merged smaller coal mines to increase their coal production capacity to 60 million tons per year without a significant reduction in capacity. Some even illegally expanded large coal mines while closing down small ones. Therefore, in order to better implement coal supply-side reforms and eliminate backward production capacity, it is necessary to analyze from the coal enterprise execution level. Given that coal enterprise plays an important role in the implementation of capacity reduction, this paper propose a multi-objective model for the allocation of de-capacity quota based on the enterprise decision-making level that considers ecological, economic, and efficiency factors. The ecological benefits, economic cost, and production efficiency of coal enterprises are important influencing factors related to the development of enterprises. Some researches have conducted analysis on these factors, Li et al. calculated the environmental losses caused by over-mining, found that environmental losses caused by coal mining took up approximately 2.7 % of the average price of coal. Wang et al. regarded improving the ecological benefits of mining areas as one of the government’s decision-making targets for de-capacity, and proved its reliability. Furthermore, Wang et al. put forwards a strategy for the allocation of de-capacity quotas that comprehensively considers economy, efficiency and fairness, and obtained reasonable conclusions. These demonstrated that the ecological, economic, and efficiency factors associated with coal overcapacity were issues of common concern to the society, which should also be the focus of coal enterprise.

The main contribution in this paper can be summarized as follows: (1) An multi-objective model based on enterprise decision-making level for coal de-capacity quota allocation is developed, which provides a effective tool for the coal enterprises to make decisions in better achieving the de-capacity reform implementation. (2) A trade-off among ecologic benefits, economic cost and production efficiency is reached among multiple mines in the process...
of overcapacity reduction implementation. (3) By comparing with the government’s allocation plan of coal de-capacity in mining areas, the superiority of the allocation strategy at enterprise’s decision level is verified from the ecologic, economic and efficient aspects. (4) Scenario analysis of the coal mine interval allocation strategy with the change of decision preference has been carried out, the results prove the stability of the strategy, which in certain extent can help enterprises to make decisions.

The remainder of this paper is organized as follows. Key problem details are given in Section 2, the associated model is proposed in Section 3. In Section 4, the proposed model is applied to a real case to demonstrate its practicality, after which the results are analyzed and discussed provided in Section 5, Section 6 reports the key findings and give some policy implications. The conclusions and future research directions are given in Section 7.

2 Key Problem Statement

Before establishing the mathematical model, specific details about basic background and description are as follows:

![Figure 1. Schematic for coal de-capacity quota allocation strategy.](image)

Coal de-capacity reform implementation is a complex problem focused on effectively allocating coal capacity reduction quotas across China’s various regions. Regional coal production de-capacity allocations is an key issue which have been extensively studied. For example, Ma et al. considered the central government-level quota allocation from the perspective of efficiency and fairness [18]. Wang et al. established a model for the allocation of de-capacity quotas from the central government-level considering the economic and environment factors [17]. Since China’s local coal mine overcapacity reduction standards are uniformly arranged by local government and the overcapacity reduction policy has been implemented well in reality. However, in some regions, due to the impact of GDP-oriented assessments by local officials, as well as empolyment pressures, many enterprises have taken only superficial measures to reduce production capacity, such as encouraging the merger and reorganization of their coal-based enterprises [4]. Further, while appearing supportive of these de-capacity practices, some local enterprises and large state-owned enterprises have opposed the control measures, which means there is still a great deal of backward production capacity capacity,
the de-capacity policy has not been implemented very well at the enterprise level. Considering that the enterprise as the main executor of coal de-capacity and may have a deeper understanding of its subordinate mining areas. Therefore, the focus of this paper is on how to establish a coal de-capacity quota allocation strategy among multiple mines at the enterprise decision-making level to further explore whether the enterprise strategy preform better by comparing with the government plan, which will be help in the smooth implementation of the coal de-capacity reform.

Faced with highly competitive energy markets and strict environmental protection measures [19], coal enterprises need to find a balance between the ecology, the economy, and sustainable operating and development efficiency [20]. As mining operations have resulted in significant environmental problems in China [21], it’s important that coal enterprises establish green mining [22]. Further, coal enterprises are mainly concerned with maximizing profits, as the implementation of de-capacity reforms will lead to higher costs, it will affect the economic benefits of the enterprises, which will result in lower enthusiasm for coal enterprises to obey [17]. Although improving the internal efficiency of enterprises can also alleviate overcapacity [23], however, it is difficult for many coal enterprises to improve their pure technical efficiency in a short period of time [24]. From the perspective of capacity reduction, a reasonable de-capacity quota allocation for each mining area can ensure the maximum production efficiency of the enterprise [6]. In summary, the key problem lies in how to implement coal capacity reduction at the enterprise decision-making level to achieve the equilibrium of ecologic-economic-efficiency, and to further explore whether the enterprise strategy preform better by comparing with the government plan. Therefore, this paper proposed the method to solve the key problem and presented a related framework shown in figure. 1.

Many real-world optimization problems have several, usually conflicting objectives. Multiple conflicting objectives including ecological benefits, economic costs and production efficiency are considered in the optimization of quota allocation towards coal de-capacity reform implementation based on the enterprise decision-making level. In this paper, the ecologic benefits aspect are represented by the reduction of three wastes during coal mining, when enterprises pursue maximum ecologic benefits, it will results in a large reduction in coal capacity in heavily polluted mining areas. Therefore, Fixed asset disposal and labor dismissal costs represents economic costs will increase, which conflicts with ecological benefits. Additionally, the fundamental coal de-capacity task is to eliminate the backward production capacity to improve the coal production efficiency, therefore, the production efficiency maximization was determined as the third objective of this problem. As these objectives are usually conflicting, it is impossible to find an optimal solution for all objectives. Multi-objective methods, which have been used in many fields and found to be very effective in solving the trade-offs between different objectives, are able to better describe real-world problems [25]. For example, Xu et al. proposed a multi-objective programming approach towards the co-combustion of municipal solid waste and coal for carbon emission and verified the feasibility of eco-friendly coal blending combustion [26]. Feng et al. developed a multi-objective model to deal with the conflicts between coal and water in multiple subordinate coal mine groups [27]. Li et al. established a multi-objective model to evaluate the effects of Shanxi Province’s green development policies, taking into account the economy, environment and coal resource consumption [28]. Encouraged by these successful studies, this study applied a multi-objective method to find the trade-off among ecologic benefits, economic costs and production efficiency.
3 Modelling

In this section, a mathematical model is given for the above described ecological-economic-efficiency equilibrium-based coal de-capacity quota allocation mechanism.

3.1 Assumption and Notations

This paper selected the enterprise as the decision-making body, considering capacity reduction from a quantitative perspective is a distribution problem, the assumptions for which were as follows:

1)Under the overcapacity reduction policy, local governments will issue standards for the capacity reduction in mining areas. This paper assumes that the enterprise has the decision-making power, according to the actual operating conditions of the subordinate mining area, allocating the capacity reduction quota to the subordinate coal mines.

2)For different mining areas, we have considered resource endowments and operating conditions as much as possible. However, some factors with endogenous interference are ignored for the time being.

3.2 Coal De-capacity Quota Allocation

As the coal de-capacity implementation main body, the enterprise assigns de-capacity quotas to their multiple coal mines. While ecological protection and economic development is important for an energy enterprise [29], enterprises need to consider ecological benefits maximization, economic cost minimization and production efficiency maximization [30]. Which is the key factor affecting enterprise management, employee enthusiasm, and enterprise development. Therefore, a multi-objective model based on ecological-economic-efficiency equilibrium is established. Details for the achievement of these objectives are given in the following sub-sections.

1) Ecological Benefits

Coal enterprises are the key to controlling and reducing greenhouse gas emissions, protecting and optimizing the ecological environment, and achieving sustainable development [31], which requires enterprises to improve the ecological benefits in their coal mines. The main pollutants discharged from coal mining areas are exhaust gas, waste water, and waste residue. Therefore, the ecological benefits objective can be expressed as a reduction in the three waste emissions resulting from the coal de-capacity efforts. In this paper, \( I_i \) represents the initial coal capacity of coal mine \( i \), \( U^{a}_i \) and \( U^{b}_i \) represents the maximum and minimum capacity utilization rates of coal mine \( i \) respectively, thus \( I_i^r q_i (U^{a}_i + U^{b}_i) \) represents the amounts of coal produced in mine \( i \) after de-capacity. Assuming \( C_i^r \) represents the emissions coefficient for these three wastes, the mathematical form can be described as:

\[
\max F_1 = \sum_{i=1}^{n} I_i^r q_i \frac{(U^{a}_i + U^{b}_i)}{2} C_i^r.
\]

2) Economic Costs

The implementation of the coal de-capacity reforms will inevitably result in economic costs, such as the dismissal of workers and fixed asset disposal costs. The enterprise wishes to minimize the labor and fixed asset disposal costs, as coal mine production facilities are of limited use and the labors are of limited skills, it is difficult to transfer these assets and human resources to other industries after mine closures [32]. Let the labor input and fixed assets input before the coal de-capacity in mine \( i \) represented by \( L_i^{in} \) and \( F_i^{in} \), \( C_i^l \) and \( R_i^l \) are the unit
labor disposal costs and loss rate of the fixed assets in coal mine $i$ respectively. Therefore, the mathematical form can be written as:

$$
min F_2 = \sum_{i=1}^{n} (L_i + C_i + R_i) q_i.
$$

(3) Production Efficiency

The fundamental coal de-capacity task is to eliminate the backward production capacity to improve the production efficiency of the coal industry [6]. In this paper, DEA model was applied to the efficient quota allocation of coal de-capacity, the coal capacity reduction evaluation principle diagram for which is shown in figure. 2, for which it was assumed that $n$ coal mines need to carry out the coal capacity reduction work, with each coal mine having $s$ inputs and $m$ output indicators. That is: $X_i = (X_{i1}, X_{i2}, ..., X_{is}), Y_j = (Y_{j1}, Y_{j2}, ..., Y_{jm})$, where $v_k$ and $u_r$ were the weights of the $k$th input and $r$th output, and $\theta_i^{Efficiency}$ was the efficiency for the $i$th DMU. A set of common weights were used in the model to evaluate the input-output efficiencies of the coal industry in the different regions; as this is a dual model, it can be expressed as follows:

$$
min F_3 = \sum_{i=1}^{n} \frac{\theta_i^{Efficiency}}{n}, \tag{3}
$$

s.t. $\begin{align*}
\sum_{i=1}^{n} \lambda_{i} X_{ij} & \leq \theta_i^{Efficiency} X_{ij}, \forall j = 1, 2, 3. \\
\sum_{i=1}^{n} \lambda_{i} Y_{ik} & \geq Y_{ik}, \forall k = 1, 2.
\end{align*}$

Coal production capacity, labor, and fixed assets were chosen as the input indicators, and net profit and raw coal production were chosen as the output indicators. Then, the production efficiency changes in $n$ coal mines were analyzed to optimize production efficiency.

![Figure 2. Schematic diagram of production efficiency optimization.](https://doi.org/10.1051/e3sconf/202340903011)

(4) Social Responsibility

**Coal Supply and demand.** As basic coal supply is a fundamental social responsibility for coal enterprises. To ensure stable production, each coal mine needs to meet certain output requirements. Suppose $M_i^e$ is the estimated coal output value at mine $i$, let $\alpha$ represents the
changes of market demand of coal, the value of $\alpha$ is zero initially. Therefore this constraint can be written as:

$$(1 + \alpha)M_i^o / U_i^b \leq I_i^c (1 - q_i) \leq (1 + \alpha)M_i^o / U_i^u, \forall i = 1, 2, ..., n. \quad (4)$$

**Total de-capacity task.** In order to smoothly implement the overcapacity reduction policy at the enterprise level, enterprise need to allocates de-capacity quota to different coal mines. To meet the total coal de-capacity reduction objective, suppose that $T^c$ represents the overall coal capacity reduction task, there are $n$ coal mines, where $q_i$ represents the coal de-capacity proportion at mine $i$. Therefore this constraint is formed as:

$$\sum_{i=1}^{n} I_i^c q_i \geq T^c. \quad (5)$$

**Quota range.** Each coal mine of the enterprise should undertake a certain amount of responsibility for capacity reduction. Assuming that $D'_i$ represents the minimum value of de-capacity quota for mining area $i$, which was decided by enterprises from the perspective of fairness and efficiency. Therefore, this limitation is formulated as:

$$I_i^c q_i \geq D'_i, \forall i = 1, 2, ..., n. \quad (6)$$

**(5) Profitability**

**Coal profit.** To ensure stable enterprise development, coal enterprise make decisions to maximize profits, coal mines after de-capacity should also enable enterprises to achieve certain profit targets. In this paper, the profits are mainly from coal-related income, suppose $E^c$ is the profit to be achieved at coal mine $i$, with $P_i^c$ being the profit value created by a unit of coal, thus, this objective can be described as:

$$\sum_{i=1}^{n} I_i^c (1 - q_i) \left(\frac{U_i^a + U_i^b}{2}\right) P_i^c \geq E^c. \quad (7)$$

**De-capacity cost.** Cost is a key enterprise factor, which means that the labor and fixed assets disposal cost resulting from the de-capacity implementation should be controlled within the scope of the enterprise budgets. Therefore, enterprises must consider the disposal costs and seek to contain them within a certain range, that is, the total cost of de-capacity should not exceed a certain value:

$$\sum_{i=1}^{n} (L_i^{ln} C_i^l + R_i^{fn} F_i^{ln}) q_i \leq E^c. \quad (8)$$

**(6) Environmental Protection**

As many hazardous pollutants such as waste gas, waste water, waste residue are discharged, the coal mining area must comply with the relevant pollutant emission legislations. Coal mining enterprises need to take responsibility for environmental protection. Therefore, the long-term development of coal mining areas requires that the coal mining waste emissions be controlled within a certain range [33].

**Waste water.** The ecological damage caused by coal mines is quite serious, with research finding that for every 1 tonne of coal mined, 2.48 cubic meters of water is polluted [34]. Let $W_i^w$ represents the waste water discharge coefficient of coal mine $i$, $T^w$ represents the total emission limit of waste water, after coal de-capacity, enterprises need to consider the ecological benefit constraints to ensure the waste water emissions are within a controllable range, therefore this constraint is written as:

$$\sum_{i=1}^{n} \left(\frac{U_i^a + U_i^b}{2}\right) I_i^c (1 - q_i) W_i^w \leq T^w. \quad (9)$$
Waste gas. Coal mining waste gas comes mainly from coal bed methane and coal gangue releases, industrial soot, \(SO_2\), and dust [3]. \(W_i^g\), which represents the exhaust emissions coefficient at coal mine \(i\), and \(T^g\) be the minimum emissions value to be controlled, this objective can be described as:

\[
\sum_{i=1}^{n} \frac{(U_i^a + U_i^b)}{2} I_i^g(1 - q_i)W_i^g \leq T^g. \tag{10}
\]

Waste residue. Waste residue is mainly coal gangue and coal ash; therefore, assuming that \(W_i^r\) is the conversion coefficient for industrial solid waste production minus the industrial solid waste utilization in coal mine \(i\), \(T^r\) is the maximum waste residue discharge limit, combining these, the constraint is formed as:

\[
\sum_{i=1}^{n} \frac{(U_i^a + U_i^b)}{2} I_i^r(1 - q_i)W_i^r \leq T^r. \tag{11}
\]

3.3 Global Model

A multi-objective model for quota allocation towards coal de-capacity implementation based on the enterprise decision-making level is established. The enterprise develops an coal de-capacity quota allocation with the aim of optimizing its ecological benefits maximization in mining area, economic costs minimization and production efficiency maximization as described in Eqs. (1)-(3), by considering its social responsibility, profitability, and environmental protection, as outlined in Eqs. (4)-(11). Therefore, the global mathematical model is formulated as Eqs. (14).

\[
\begin{align*}
\max F_1 &= \sum_{i=1}^{n} I_i^c q_i \frac{(U_i^a + U_i^b)}{2} C_i^c. \\
\min F_2 &= \sum_{i=1}^{n} (L_i^m C_i^l + F_i^m R_i^a) q_i. \\
\min F_3 &= \sum_{i=1}^{n} \theta_i \text{Efficiency} / n. \\
\begin{aligned}
\sum_{i=1}^{n} a_i X_{ij} &\leq \theta_i X_{ij}, \forall j = 1, 2, 3. \\
\sum_{i=1}^{n} a_i Y_{ik} &\geq Y_{ik}, \forall k = 1, 2. \\
(1 + \alpha)M_i^p / U_i^b &\leq I_i^r(1 - q_i) \leq (1 + \alpha)M_i^p / U_i^a. \\
\sum_{i=1}^{n} I_i^c q_i &\geq T^c. \\
I_i^r q_i &\geq D_i^r. \\
\sum_{i=1}^{n} I_i^r(1 - q_i) \frac{(U_i^a + U_i^b)}{2} P_i^c &\geq E^c. \\
\sum_{i=1}^{n} (L_i^m C_i^l + F_i^m R_i^a) q_i &\leq E^c. \\
\sum_{i=1}^{n} \frac{(U_i^a + U_i^b)}{2} I_i^r(1 - q_i)W_i^g &\leq T^w. \\
\sum_{i=1}^{n} \frac{(U_i^a + U_i^b)}{2} I_i^r(1 - q_i)W_i^g &\leq T^q. \\
\sum_{i=1}^{n} \frac{(U_i^a + U_i^b)}{2} I_i^r(1 - q_i)W_i^r &\leq T^r. \\
\forall i = 1, 2, ..., n.
\end{aligned}
\end{align*}
\]
3.4 Model Transformation and Solution Approach

To deal with the trade-off among ecological benefits, economic cost and production efficiency, this paper establishes a multi-objective model. Membership function method, which unifies the multiple objectives that have different dimensions into a dimensionless single objective, provides a basic and easy approach for multi-objective optimization [35]. Before using the membership function method, θ was applied to measure the objective of production efficiency ($\theta_i \geq 1 (\forall i = 1, 2, ..., n)$), and the other two objective functions were standardized, which is conducive to linear weighting. Therefore, the integrated single-objective function can be formulated as:

$$\max F_{equal} = \{ \omega \left( \frac{F_1 - F_{min}^1}{F_{max}^1 - F_{min}^1} \right) + (1 - \omega) \frac{F_{max}^2 - F_2}{F_{max}^2 - F_{min}^2} \}. \tag{13}$$

Where Z is the equality objective function for the enterprise. $\omega$ and $(1 - \omega)$ are the weighting coefficients to represent the enterprise’s preference to ecological benefits and economic costs. $F_{min}^1$, $F_{min}^2$ represent the minimum values of the objectives, and $F_{max}^1$, $F_{max}^2$ represents the maximum values. Using the membership function method, the multi-objective is transformed into a single-objective model in Eq. (14).

By converting the efficiency objective into a constraint and using the membership function method, the ecological and economic objectives were unified into a single objective, and the global model transformed into its equivalent single form. Lingo software, which can easily analyze, modify, and solve mathematical optimization problems, has been proven to be very effective in solving single objective models [36]. Therefore, LINGO18.0 was chosen to solve the single objective model.

$$\max F_{equal}$$

s.t. \begin{align*}
\theta^\text{Efficiency}_i & \geq 1. \\
\text{Eq.(4)} - \text{Eq.(11)}. \tag{14}
\end{align*}

4 Case Study

In this section, a practical example from the Yankuang Group in Shandong Province is given to demonstrate the practicality and efficiency of the proposed optimization model.

4.1 Case Description

Shandong Province, which is located in the northeast of China, is known for its major energy and chemical production and rich coal resources. The Yankuang Group (YK Group) is located in southwest Shandong Province at one of the largest coal fields in China [37]. However, a productivity efficiency and ranking survey of China’s major coal production regions from in recent ten years found that although Shandong province was a main coal production area, its coal production capacity utilization rate was relatively low [38]. Therefore, the implementation of coal de-capacity in Shandong Province is of great significance. YK Group, which has an important position in the Shandong province coal industry, has many coal mines and rich resources. Therefore, YK Group plays an important positive and guiding role in the coal de-capacity policy implementation.

Based on the above situation, the YK Group was selected as the case study to verify the effectiveness of the proposed de-capacity quota allocation method. To reduce the calculations,
only nine YK Group coal mines were selected as examples; Nantun (NT), Xinglongzhuang (XLZ), Baodian (BD), Dongtan (DT), Jining No.2 (JN No.2), Jining No.3 (JN No.3), Yangcun(YC), Zhaolou(ZL) and BeiXiu(BX).

4.2 Data Collection

In 2016, the State Council issued opinions on resolving excess capacity and realizing coal industry development by withdrawing 800 million tonnes of coal production capacity during the ‘13th Five-Year’ period. The Shandong Coal Industry Bureau has issued a detailed annual notice of mining capacity reduction. The official website shows the amount of coal that YK group expected to sell each year. The China Coal Industry Statistics Yearbook reported the annual output of coal in YK Group. YK Group has nine main coal mines in Shandong Province, which also occupy the group’s main coal mining business. Therefore, it was assumed the nine coal mines account for 80% of the enterprise’s total coal production. Because of the various coal types; coking coal, anthracite, lean coal, etc.; this paper comprehensively considered all types. The annual report on the construction of high safety coal mines in China’s coal industry reported the annual coal output in each mining area. As the capacity utilization is equal to the ratio of actual production to actual production capacity, based on the comprehensive production performance of several major mining areas over the years, the productivity utilization rate was estimated, and the other relevant parameters obtained from the China Coal Industry Statistics Yearbook. The Shandong Provincial Development and Reform Commission gave several energy development suggestions for the coal capacity reduction, which were also used in this paper, some data for which are shown in table 1 and table 2.

Table 1. Parameters of Yk Group

<table>
<thead>
<tr>
<th>Total target</th>
<th>Expected profit</th>
<th>Limit emission of waste water</th>
<th>Limit emission of waste gas</th>
<th>Limit emission of waste residue</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T^*$ (10^6 tonnes)</td>
<td>$E^*$ (10^9 RMB)</td>
<td>$T^w$ (10^7 tonnes)</td>
<td>$T^g$ (10^7 tonnes)</td>
<td>$T^r$ (10^7 tonnes)</td>
</tr>
<tr>
<td>2.60</td>
<td>2.00</td>
<td>6.50</td>
<td>5.50</td>
<td>7.50</td>
</tr>
</tbody>
</table>

Table 2. Parameters of each coal mine

<table>
<thead>
<tr>
<th>Coal mine</th>
<th>Original capacity $I_i$ (10^6 tonnes)</th>
<th>Capacity utilization $U_i$</th>
<th>Yield requirements $M_i$ (10^6 tonnes)</th>
<th>Labor input $L_i$ (10^4 people)</th>
<th>Fixed assets $F_i$ (10^8 RMB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NT</td>
<td>3.00</td>
<td>(60,65)</td>
<td>2.02</td>
<td>0.56</td>
<td>2.70</td>
</tr>
<tr>
<td>XLZ</td>
<td>6.50</td>
<td>(68,73)</td>
<td>4.50</td>
<td>0.69</td>
<td>6.80</td>
</tr>
<tr>
<td>BD</td>
<td>6.40</td>
<td>(60,70)</td>
<td>4.44</td>
<td>1.00</td>
<td>9.00</td>
</tr>
<tr>
<td>DT</td>
<td>7.50</td>
<td>(65,75)</td>
<td>2.77</td>
<td>1.50</td>
<td>7.50</td>
</tr>
<tr>
<td>JNNo.2</td>
<td>4.20</td>
<td>(70,85)</td>
<td>2.91</td>
<td>0.90</td>
<td>5.50</td>
</tr>
<tr>
<td>JNNo.3</td>
<td>6.50</td>
<td>(67,77)</td>
<td>4.50</td>
<td>1.02</td>
<td>4.20</td>
</tr>
<tr>
<td>YC</td>
<td>5.00</td>
<td>(69,73)</td>
<td>3.47</td>
<td>0.83</td>
<td>3.90</td>
</tr>
<tr>
<td>ZL</td>
<td>3.36</td>
<td>(70,75)</td>
<td>2.33</td>
<td>0.83</td>
<td>3.90</td>
</tr>
<tr>
<td>BX</td>
<td>1.00</td>
<td>(50,60)</td>
<td>1.45</td>
<td>0.04</td>
<td>3.00</td>
</tr>
</tbody>
</table>

5 Results and Discussion

This section analyzes the ecological, economic, and efficiency aspects of the optimal coal de-capacity quota allocation strategy, and calculates the changes in the optimal allocation strategy under different decision maker’s preferences and the impact of changes in coal market demand on the quota allocation decisions and objectives by the enterprise decision makers.
5.1 Optimal Allocation of Coal De-capacity for Coal Mines

This section discusses the influence on the allocation decisions and the objectives when the decision makers’ preferences changed.

It was assumed that the enterprise had the same preferences for its ecological benefits and economic cost coal de-capacity objectives, with \( \omega = 0.5 \), \( (1 - \omega) = 0.5 \). Solving model Eq. (14), the optimal quota allocation scheme was obtained from the capacity reduction scale, proportion and its allocation ratio of the total overcapacity reduction task, as shown in figure 3.

Fig. 3 shows the coal de-capacity quantities and proportions in the nine coal mines under its same preference, from which it can be seen that the coal production capacity reduction allocations varied significantly across the mines. Under the same preference, there were three mines with more than a 0.5 million tonnes coal capacity reduction, namely XLZ, BD and JN No.3, which accounted for 57.7% of the total task, with the four other mines, JN No.2, ZL, BX; having less than a 0.1 million tonne coal production capacity reduction and the least proportions of 0.50%, 0.38%, and 3.85%. These results indicated that under the ecological, economic and efficiency principles, several of the large coal mines undertook the majority of the coal production capacity reductions. Interestingly, even when two coal production mines had similar coal production capacities, the de-capacity allocations varied significantly because of the differences in the two coal mines. For example, NT and ZL had the similar coal production capacities of 3 million tonnes per year. However, the asset loss rate in ZL was also higher than in NT and the pollution degree at NT was more serious than in ZL. Therefore, based on the ecological and economic principles, the coal production capacity reduction in NT should be higher than in ZL.

Under the same preference, the larger coal production mines DT(5.86%) had smaller capacity reduction scales, and the smaller and older coal production mines, such as NT(10%) and BX(10%), had a heavier capacity reduction. There were various reasons for the above results, one of which was that the large coal mining areas have greater coal production capacity, and tend to have higher mechanization levels, more abundant coal reserves, and relatively small backward capacity. Therefore, under the efficiency principle, their reduction scale was lower, whereas the smaller coal mines have less coal resources, find it more difficult to attract investment than the larger coal enterprises, have lower mechanization, and have a higher resource exhaustion due to long-term coal mining, which means that in the face of fierce market competition, their profitability is very low, which indicated that when seeking to optimize
coal capacity reduction allocations, these mines should reduce a more of their coal production capacity compared to other mines.

5.2 Comparative Analysis

In order to research the effectiveness and rationality of the enterprise’s decision-making plan for the de-capacity quotas allocation to its subordinate mining areas, this paper considers the relevant government departments’ plan for overcapacity reduction in specific coal mines from during the ‘Thirteen-Five’ period, and conducts a comparative analysis in terms of ecologic, economic, and efficiency.

According to the government’s plan to reduce overcapacity in the mining area, the mining areas with the largest amount of capacity reduction in YK Group are BX, XLZ, and JN No.3 and account for 38.50%, 19.23%, and 19.23%, respectively, which total accounting for approximately 80% of the YK group’s overall capacity reduction tasks. Under the arrange-

![Figure 4. Allocation ratio among multiple mines under different plan](image)

Compared with the government plan in overcapacity reduction, the ecological benefits of enterprise plan have significantly improved. It can be seen in Fig. 5 that the ecological benefits of enterprise plan are 4.69 million tonnes higher than those of government plan. There are four coal mines with improved ecological benefits based on the enterprise plan, which are BD, DT, YC, ZL. Among them, BD and DT has the biggest improvement in ecological benefits, the reason is that pollution in these mining areas are more serious, and the means of reducing overcapacity can reduce the harm to the environment caused by excessive coal mining. In addition, the ecological benefits of some other coal mines have decreased in the enterprise plan, as shown in Fig. 5. However, on the enterprise decision-level, the capacity reduction of each mining area is allocated, and the environment of each mining area can be governed to a certain degree, thus the cumulative environmental benefits have been significantly improved.
6 Key Findings and Policy Implications

This section discusses the key findings of calculation results and gives some policy implications.

6.1 Key Findings

Because of the current de-capacity urgency in China’s coal industry enterprises, this paper developed a multi-objective mathematical model for quota allocation based on the enterprise decision-level towards coal de-capacity implementation. In this model, the decision maker sought to maximize the ecological benefits, minimize the de-capacity economic costs, and improve coal enterprise production efficiency. In order to verify the effectiveness of enterprise’s strategy, we compare the results of enterprise’s strategy with government from the aspects of ecological benefits and economic costs. In addition, the optimal coal de-capacity quota allocation scheme was calculated under different target preferences to analyze the changes of overcapacity reduction strategies, the main conclusions from which were as follows.

- The proposed coal de-capacity quota allocation mechanism can trade off the ecological and economic benefit and the production efficiency. Due to the differences in resource endowments, the ecological and economic level among various coal mines, the assigned tasks of overcapacity reduction are also different. To be specifically, mining areas with larger coal production capacities generally have higher mechanization, more abundant coal reserves, and relatively small backward production capacity; therefore, their capacity reduction scales are relatively small compared with other mines. However, small scale coal mines have less coal resources, find it difficult to attract investment from large coal enterprises, have low mechanization, and nearly exhausted resources, when seeking to optimize the coal de-capacity allocations, these coal mines should have larger scale reductions compared with other mines. Therefore, the comprehensive evaluation among multiple mines will better help to promoting the implementation of coal de-capacity reform in various coal mines.

- Compared with the government plan in allocating de-capacity quotas among multiple mines, the enterprise’s strategy has better ecological benefits in mining areas, lower economic costs of capacity reduction, which can better balance the equilibrium between ecological and economic. To be specifically, the total economic costs of the enterprise’ strategy is 42.79 million CNY lower than that of the government. The ecological benefits of the enterprise’ strategy is 4.69 million tonnes higher than that of the government. In addition,
although the production efficiency calculated by different indicators are different, the DEA efficiency of the enterprise's strategy is higher than 1, which indicated that the internal and external conditions after coal de-capacity were relatively coordinated.

• The model has good internal consistency and can provide a certain reference for enterprise decision-makers. Although there were some differences in the coal de-capacity quota allocations between the multiple mines under the different preferences, the trend change was consistent with the actual situation. Specifically, under the economic preference scenario, the coal mines that had a higher growth in economic costs had a lower de-capacity proportion, and the coal mines with a smaller increasing rate in economic costs had a greater de-capacity scale. Under the ecological preference scenario, the coal mines that had larger ecological growth benefits had greater de-capacity proportions, and the coal mines with smaller ecological benefits growth had lower de-capacity proportions.

6.2 Policy Implications

Based on the above analysis, this section proposes some policy implications from enterprise, industry, and government perspectives to better explore the implementation of China’s coal capacity reduction reforms.

• Coal enterprises should formulate environmentally friendly, economic, and effective coal de-capacity quota allocation plans to ensure the smooth implementation of the coal de-capacity policies. Due to differences in ecological protection and development in the different mining areas, efforts to reduce production capacity can be increased in mining areas with low production efficiency and serious environmental pollution. In production mining areas with higher efficiency, the capacity reduction could be reduced as appropriate and the capacity allocation increased to ensure regional economic and social development and stabilize the coal supply.

• In the coal industry, the construction of large coal bases should be accelerated and the smaller coal mines with poor conditions phased out. The study results showed that the production capacity reductions in large-scale, highly efficient mining areas were relatively smaller compared to low-efficiency mines, but the potential for these mining areas to supply the needed coal supply to the market was relatively large. Therefore, the coal industry should focus on existing coal resource management relationships to promote the advantageous resources in large mines, increase the effective utilization of coal resources, and change the situations in large coal enterprises with low coal resource security and a shortage of reserve resources.

• In line with the actual situations in the regions, the government should make overall plans for the economic development and the ecological benefits by formulating coal de-capacity quota allocation plans that match current development, concentrating advanced coal production in advantageous enterprises and regions. Because of the enterprise resource endowment and economic development differences, the principle of fairness needs to be followed to ensure the smooth implementation of the coal capacity reduction reforms. Taking into account the differences between different enterprises and different mine areas, formulating targeted measures to reduce overcapacity to prevent one size fits all.

7 Conclusions and Future Study

This paper developed a multi-objective mathematical model for quota allocation based on the enterprise decision-level towards coal de-capacity implementation. As the main implementor of coal de-capacity, the enterprise addressed the allocation of coal de-capacity quota,
to achieve its objectives of ecological benefits maximization, economic costs minimization and production efficiency maximization. The proposed multi-objective mathematical model were transformed into a solvable single-objective model using membership function method. The application of the model to YK group was conducted to show its practical applicability and efficiency. It could be found from the calculation results that the proposed model effectively solved the coal de-capacity implementation problems through enterprises allocates quotas to mining areas and reach the ecologic-economic-efficiency equilibrium. It was also conducted that to effectively achieve coal de-capacity on the enterprise level it was necessary to allocate greater quotas to lower production efficiency mining areas. By conducting comparison between enterprise’s strategy and the government, we verified the superiority of the allocation scheme on the enterprise decision-level. Sensitivity analysis on the decision makers’ preferences was conducted to prove the reliability of results and the internal consistency of model. Moreover, compared with previous relevant researches, this study focused on the problem from enterprises perspective and determined a rational coal de-capacity quota allocation, which can better help the enterprises in de-capacity reform implementation, enhancing the enthusiasm of mining areas to reduce production capacity. Finally, policy implications from enterprise, industry and government level are given to better solve the coal overcapacity problem.

In future studies, the proposed model could be improved to consider dynamic factors such as how to execute it dynamically in time scale. and a more comprehensive and realistic optimization method with a wider scope of application will be investigated to address the coal de-capacity reform implementation.

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