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Equilibrium Strategy Based Recycling Facility Site Selection towards Mitigating Coal Gangue Contamination

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Abstract: Environmental pollution caused by coal gangue has been a significant challenge for sustainable development; thus, many coal gangue reduction approaches have been proposed in recent years. In particular, coal gangue facility (CGF) construction has been considered as an efficient method for the control and recycling of coal gangue. Meanwhile, the identification and selection of suitable CGF sites is a fundamental task for the government. Therefore, based on the equilibrium strategy, a site selection approach under a fuzzy environment is developed to mitigate coal gangue contamination, which integrates a geographical information system (GIS) technique and a bi-level model to identify candidate CGF sites and to select the most suitable one. In this situation, the GIS technique used to identify potential feasible sites is able to integrate a great deal of geographical data to fit with practical circumstances; the bi-level model used to screen the appropriate site can reasonably deal with the conflicts between the local authority and the colliery. Moreover, a Karush–Kuhn–Tucker (KKT) condition-based approach is used to find an optimal solution, and a case study is given to demonstrate the effectiveness of the proposed method. The results across different scenarios show that appropriate site selection can achieve coal gangue reduction targets and that a suitable excess stack level can realize an environmental-economic equilibrium. Finally, some propositions and management recommendations are given.

Keywords: coal gangue contamination; recycling facility; site selection; equilibrium strategy; environmental improvement

1. Introduction

Coal is one of the main resources in the world, especially in developing countries [1–4]. For example, China is one of the largest coal producing countries, with coal accounting for 67.5% of the primary energy supply [5]. Coal gangue, a by-product of coal mining and washing, is a major solid waste [6–10] that not only occupies plenty of land, but also results in a series of environmental problems, such as the water, soil and atmospheric pollution [11–15]. Therefore, under pressure from increased coal consumption and the subsequent increased environmental pollution, there is an urgent need to control coal gangue contamination.

Some methods have been proposed to reduce the adverse effects from coal gangue and to utilize coal gangue. Zhang et al. [16] developed an approach using coal gangue to backfill mining, which has been proven to be effective in controlling coal gangue contamination. Coal gangue can be used to produce glass ceramics with coal gangue accounting for 70% of the starting material [17]. Wang et al. [18] proposed a new type of autoclaved aerated concrete using coal gangue. In addition, coal gangue can also be used in the cement industry to replace clay as a raw material [19]. Further, governments and agencies around the world have developed policies and laws to mitigate the harmful influence of gangue piles, such as the Chinese Management Measures for the Comprehensive Utilization of Coal Gangue, the German's Dual Recovery System (DSD) Mode and the Pollution Prevention Law of the United States. Though the undesirable impacts of gangue piles has been alleviated somewhat through the use of recycling technologies and government policies, the coal gangue utilization rate is still less than 15% in China [20]. In addition, regardless of these policies, the environmental problems caused by coal gangue are still serious [21–23]. Therefore, it is necessary to determine other feasible methods for dealing with coal gangue. Constructing a coal gangue facility (CGF) in coal fields based on gangue-by-gangue characteristics has been proposed as a reasonable method to improve coal gangue utilization efficiency and to realize stack reduction targets [24–26], but few studies have considered the coal gangue pollution problem from a managerial point of view. To ensure a more effective CGF, the identification and selection of suitable sites is fundamental, which affects both the environment and the recycling efficiency of coal gangue.

Appropriate CGF site identification and selection require the consideration of many factors, such as transportation conditions, costs, local geographical characteristics, development planning and environmental pollution. As a result of this complex, but important decision process, there has been increased research on site selection in recent years. Avittathur et al. [27] developed non-linear mixed integer programming to select the optimal location for a distribution center with different sales tax structures. A mean-shift algorithm was proposed by He et al. [28] to solve large-scale planar maximal covering location problems. Gołębiewski et al. [29] established a non-linear modeling to determine vehicle recycling facility site selection by defining the most suitable dismantling facilities sites. To reduce the effects of unexpected disasters, a stochastic modeling framework was proposed to decide the location and capacities of distribution centers for emergency stockpiles [30]. Meanwhile, some scholars attempted to solve the site selection problem by GIS. Aydin et al. [31] developed a decision tool using GIS for the hybrid wind solar-PV renewable energy systems location problem. Taking landslide exposure into consideration, Mahnaz et al. [32] proposed to mask unsuitable areas using GIS for selecting waste disposal sites. Latinopoulos et al. [33] integrated a methodology by combining the spatial multi-criteria decision analysis and GIS for wind-farm planning at the regional level. This application of GIS in the location problem has received considerable attention, which ignored the inherent relationship among multi-decision makers. In addition to these approaches, other methods, such as bi-level programming, have been applied to the site selection problem. Supalin et al. [34] selected the optimal site for production distributions and distribution centers via a bi-level programming model. Considering benefits for customers and logistics planning departments, Sun et al. [35] formulated a bi-level programming model to select the appropriate site for logistics distribution centers. With a hierarchical structure composed of a local authority and several stone enterprises, Gang et al. [36] solved a stone industrial park location problem by establishing a bi-level programming model. These studies had important impacts on optimal site selection for predetermined construction projects, which ignored the influence from geospatial data.

When considering CGF site selection approaches, many of these existing methods are not suitable for the following reasons. First, many studies have tended to identify candidate sites using only historical experience and have ignored the significant effects of geospatial data on site identification. Second, traditional site selection research has mostly included only a single decision maker; however, for CGF site selection, such an approach that only takes into account the local authority's perspectives is impractical, as the colliery decisions also influence site selection by determining optimum production and recycling quantity. Therefore, the complex interactive relationships between the local authority and the colliery need to be taken into account for CGF site selection. Third, site selection needs to include a consideration of the uncertain environment, as there are many uncertainties in large construction projects [37,38]. Taking these issues into consideration, it is, therefore, necessary to find new methods to solve the CGF site identification and selection problems. In this situation, this paper proposes an integrated method by combing a GIS technique and a bi-level programming model to identify candidate CGF sites and to select the most suitable one, which, both considering the geospatial data and inherent relationship among multi-decision makers, is more suitable for the practical CGF site selection situation.

Based on the above analysis, an optimal CGF site selection problem has two parts: identifying alternative sites and screening the most appropriate site. At the beginning, a GIS technique is used to integrate geospatial data so as to screen candidate sites, a technique that has been applied successfully to site identification in many projects [39]. Once alternative sites have been identified, a bi-level multi-objective programming (BLMOP) model with fuzzy variables is formulated to determine the optimal site. In this situation, the bi-level model describes the conflicts between the government and each colliery. In addition, a multi-objective technique is applied to find the equilibrium between environmental protection and economic development, and the uncertain environment is dealt with using fuzzy theory [40].

The structure of this paper is as follows. Section 2 gives the detail of the CGF site selection problem. A GIS-modeling approach towards the CGF site screening problem and a solution approach based on the KKT condition are proposed in Section 3. Section 4 gives a case study in the Yanzhou coal field, and then, some propositions and management recommendations are proposed in Section 5. Finally, conclusions are presented in Section 6.

2. Key Problem Statement

From a development view point, an effective site identification and selection strategy is needed, as an unsuitable site may lead to a coal supply shortage in the local area and a failure to mitigate coal gangue contamination.

The CGF site identification system requires significant geospatial data, such as geological fault data, climatic conditions and soil data. In practice, it is difficult to quantify the geospatial data spatial relationships without using the GIS technique; hence, appropriate sites should be identified using the GIS technique before optimal CGF site selection. The spatial features needed for the CGF identification are taken from Joachim et al. [39] and Qaddah et al. [41], which have been proven to be feasible in numerous large construction projects. Generally, geospatial data are of different scales when collected from different sources, increasing the complexity of the site identification process. Therefore, a spatial data modeling tool and a spatial analysis method need to be included in the GIS technique.

In the CGF site selection system, there are two kinds of decision makers: the local authority and each colliery owner. The local authority, considered as the "leader level", which represents the public and is responsible for the environmental protection and economic development, determines the site selection, with the objectives of reducing the total coal gangue stacks in the coal fields and increasing the total social revenues. The colliery owners, considered as the "follower level ", make their coal output and coal gangue transportation plans to maximize profits based on the government's site selection strategy. The conflicts are obvious: the government seeks to reduce coal gangue stack levels, while each colliery attempts to increase its coal output and to reduce the coal gangue transportation quantity. Therefore, while the authority and the colliery are both independent, there is also a mutual influence, which from the competition view point plays a key role in the CGF site selection problem. In fact, the decision-making process that has a "leader follower" relationship can be regarded as a Stackelberg game. To solve the conflicts between the government and the collieries, a bi-level model is imported to express the Stackelberg game in the CGF site selection process. The structure of the bi-level relationship between the local authority and the colliery is shown in Figure 1.

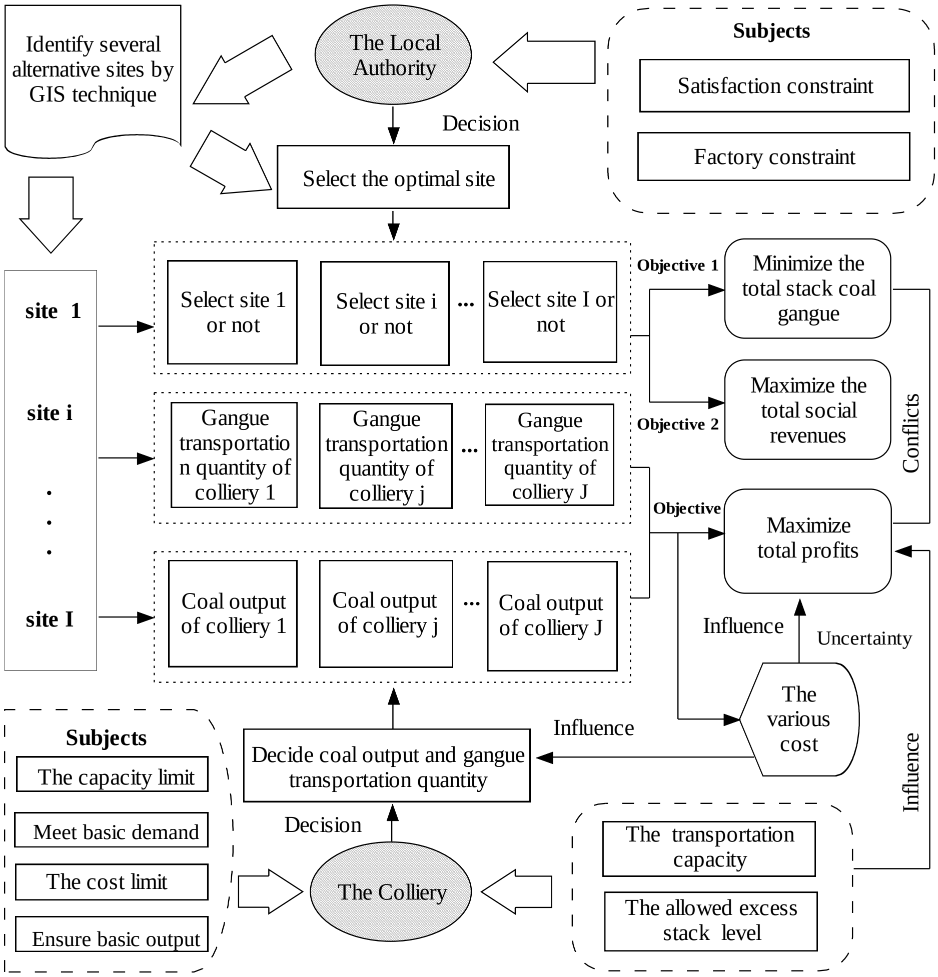

Figure 1. The bi-level relationship between the local authority and the colliery.

3. Coal Gangue Facility Siting Method

According to a GIS technique and a modeling technique, this paper formulates an integrated method to solve the complicated CGF site selection problem. A model transformation based on the KKT condition is then introduced to solve the proposed BLMOP model. The detailed discussions are in the following.

3.1. Identifying Candidate Sites Using the GIS Technique

The GIS technique provides a framework for collecting, storing, analyzing, transforming and displaying spatial and non-spatial data. In particular, it has been successfully applied to screen for the suitable seismic station sites [39] and to identify potential sites for soil and water conservation techniques [41]. Because of these successes, this paper seeks to screen for viable CGF sites based on the geospatial data GIS technique using spatial data modeling tools and a spatial analysis method, for which ArcGIS software (ArcGIS 10.2; Esri: Sacramento, CA, USA) and MapInfo are applied as the core spatial data analysis GIS platforms. Joachim et al. [39] developed a GIS framework for seismic station identification, which is used as the basis in this study for the proposed GIS based bi-level modeling method. The flowchart for the GIS-modeling technique is shown in Figure 2.

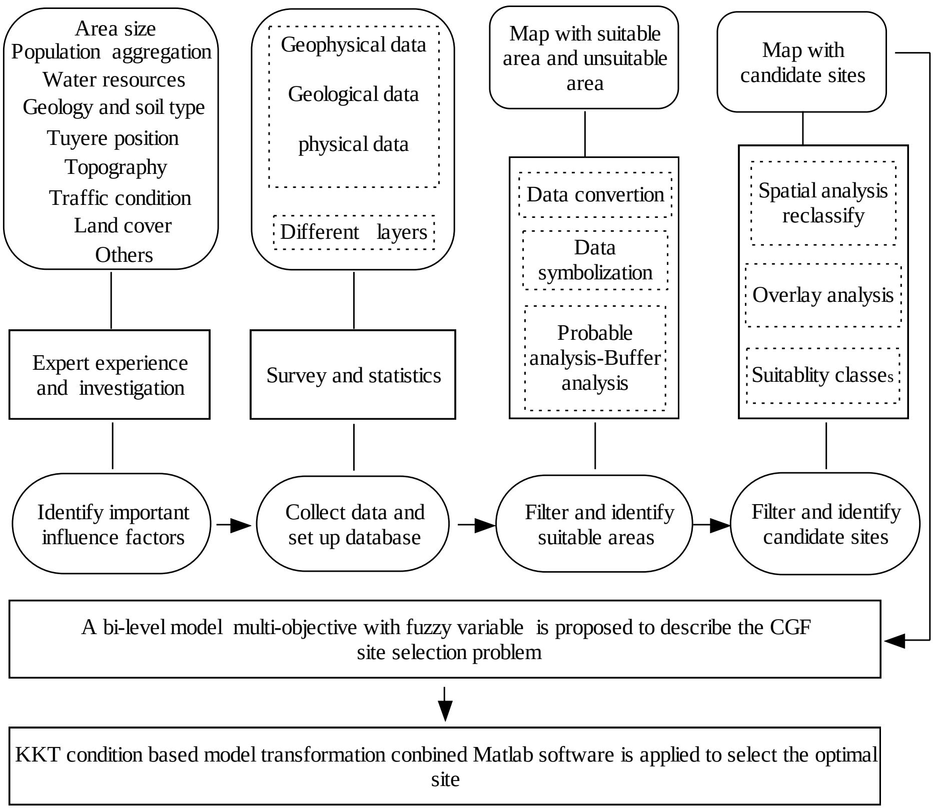

Figure 2. Flowchart for the GIS-modeling technique for the CGF site identification and selection problem.

3.2. *Selecting the Optimal Site Using the Modeling Technique*

In this section, the relevant assumptions are first outlined, then the bi-level multi-objective model for the CGF site selection problem considering uncertainty is constructed according to the identification results. The mathematical description for the problem is given as follows.

3.2.1. Assumptions

To construct a model for the CGF site selection problem, the following assumptions are adopted:

(1) The CGF's construction costs are undertaken by the local authority.
(2) The tax rate is the identical for each colliery.
(3) The CGF capacity is the same at each alternative site.

3.2.2. Notations

The following mathematical notations are used to describe the CGF site selection problem.

(1) Index:

i potential site index, where $i = 1, 2, \ldots, I$;
j colliery index, where $j = 1, 2, \ldots, J$;

(2) Certain parameters:

I number of potential CGF sites;
J number of collieries;
C_j^{basic} basic production of the colliery j;
$C_j^{capacity}$ maximum production capacity of the colliery j;
T_{ij}^{cg} volume of transportation from the colliery j to CGF i;

ϑ	economic revenue coefficient of unit ton coal gangue in the CGF;
P_j^c	sale price of unit ton coal of the colliery j;
D^{basic}	basic amount of coal that the coal field should supply;
β	satisfaction degree of the colliery;
α	the allowed stack level for the colliery;
φ	the excess stack level permitted;
H_j	historical coal gangue stack data at colliery j;
d_{ij}	distance between the CGF i and colliery j;
C_j^m	budget for colliery j;
P_s	price for unit coal gangue stack quantity;

(3) Uncertain parameters:

$\widetilde{C_j^o}$	unit operating and maintenance costs for colliery j;
$\widetilde{C_j^t}$	unit coal gangue transportation costs for the colliery j;
$\widetilde{E_j^g}$	coal gangue emission coefficient for a unit ton of coal at colliery j;

(4) Decision variables:

X_i	binary variable; if site i selected to build CGF, $X_i = 1$, otherwise $X_i = 0$;
Y_j	output decision of colliery j;
R_{ij}	coal gangue transportation quantity from colliery j to CGF i.

3.2.3. Model Formulation

To solve the complex coal gangue facility site selection problem, a bi-level multi-objective model is established from an environmental protection and economic development view point.

Coal gangue facility site selection: In the CGF-SS system, there are various factors (i.e., environmental protection and social revenue) that affect the local authority's behavior; hence, the authority seeks to achieve multiple objectives; minimizing the total coal gangue stack level and maximizing the total social revenue.

Coal gangue stack minimization: In the real world, reducing or mitigating the pollution effect on environmental and human health is one of the main objectives of the local authority; therefore, minimizing the total coal gangue stack quantity at the colliery is the first objective.

Significant research has been conducted on the coal gangue pollution problem, from which the establishment of a coal gangue facility has been found to be the best scientific reference for policymakers. According to the above assumptions, when a CGF site is identified, collieries j have a fixed transportation capacity, and each colliery decides their transportation quantities, i.e., $\sum_{i=1}^{I} X_i R(ij)$. However, as the coal quality is different in each colliery, the coal gangue production coefficient for a unit tonne of coal is also different, meaning that the production coal gangue quantity from a colliery is $\widetilde{E_j^g} Y_j$. Therefore, the coal gangue stack at the colliery j is $\left(\widetilde{E_j^g} Y_j - \sum_{i=1}^{I} X_i R(ij)\right)$.

There are in fact many factors, such as mining methods, geographical structures and processing methods, that can have a significant impact on the coal gangue emission coefficient for a unit tonne of coal at colliery j (i.e., $\widetilde{E_j^g}$). Therefore, it is difficult to estimate $\widetilde{E_j^g}$ as a certain parameter. Consistent with reality, experienced experts and engineers are asked to estimate the most likely coal gangue emission coefficient, from which a value range is determined. The minimum value is regarded as the left border (i.e., a_{1j}); the maximum value is regarded as the right border (i.e., a_{3j}); and the most possible value is a_{2j} ($a_{1j} \leq a_{2j} \leq a_{3j}$). It is reasonable to deal with this uncertainty using fuzzy theory [40], which is a triangular fuzzy number $\widetilde{E_j^g} = (a_{1j}, a_{2j}, a_{3j})$, where $a[.]$ is the parameter in the membership function for the triangular fuzzy number $\widetilde{E_j^g}$.

Because the parameter $\widetilde{E_j^g}$ is fuzzy, the objective function Z_1 is also a fuzzy goal, which can be described precisely as fuzzy sets in the spaces of the alternatives. An optimistic-pessimistic parameter is introduced using the fuzzy measure *Me* to obtain the decision maker attitudes [42] (see Figure 3). From Xu's methods, the fuzzy variable $\widetilde{E_j^g}$ can be converted into a crisp form, as follows:

$$\widetilde{E_j^g} \longrightarrow E\left[\widetilde{E_j^g}\right] = \frac{1-\lambda}{2}(a_{1j}+a_{2j}) + \frac{\lambda}{2}(a_{2j}+a_{3j}) = \frac{1}{2}\left[(a_{2j}+a_{1j}) + \lambda(a_{3j}-a_{1j})\right]. \tag{1}$$

Thus, the optimal CGF site minimizes the total piled coal gangue quantity, which can be expressed as follows:

$$\min_{X_i} Z_1 = \sum_{j=1}^{J}\left(E\left[\widetilde{E_j^g}\right]Y_j - \sum_{i=1}^{I} X_i R(ij)\right). \tag{2}$$

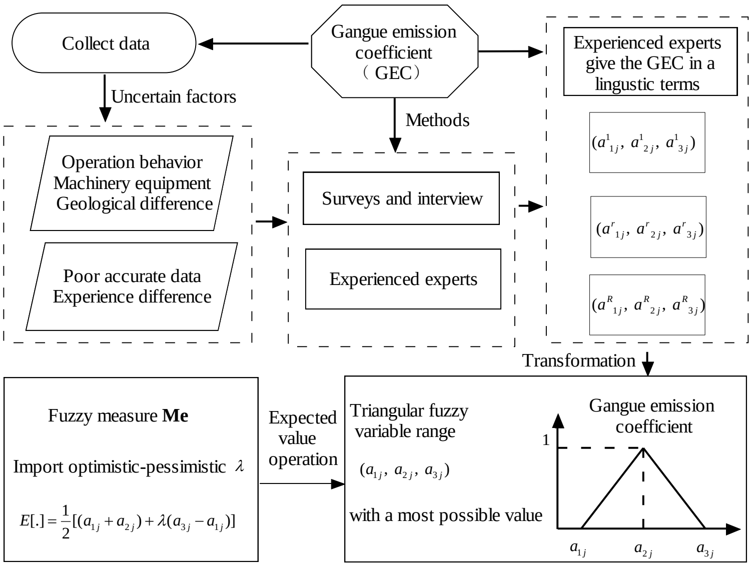

Figure 3. Flowchart for the expected fuzzy coal gangue emissions coefficient.

Total social revenue maximization: Seeking to reduce the adverse effects from the coal gangue piled at different collieries, the local authority is also seeking to maximize total social revenue, which includes the coal gangue-related revenue and tax revenue. The coal gangue-related revenue is made up of stack revenue and the CGF revenue. If the stack revenue is a positive value, it indicates that the initial allowed stack level is not sufficient for the colliery j; if the stack revenue is a negative value, it indicates that the coal gangue stack quantity is less than the initial allowed stack level, i.e., $\left[\left(E\left[\widetilde{E_j^g}\right]Y_j - \sum_{i=1}^{I} X_i R(ij)\right) - \alpha H_j\right]P_s$. As a possible renewable resource, the coal gangue processed at the CGF is also revenue producing, which is an important factor for the local authority. The economic revenue coefficient for a unit of coal gangue at the CGF is ϑ; thus, the CGF revenue can be expressed as: $\vartheta \sum_{j=1}^{J}\sum_{i=1}^{I} X_i R_{ij}$. Let ψ be the tax rate, P_j^c be the sale price of the colliery j and Y_j be the coal output decided by the colliery owner; hence, the taxes revenue is $\sum_{j=1}^{J} \psi P_j^c Y_j$. As the aim of the local authority is to maximize total revenue, the objective function is described as:

$$\max_{X_i} Z_2 = \sum_{j=1}^{J}\left[\psi P_j^c Y_j + \vartheta \sum_{i=1}^{I} X_i R_{ij} + \left(\left(E\left[\widetilde{E_j^g}\right]Y_j - \sum_{i=1}^{I} X_i R(ij)\right) - \alpha H_j\right)P_s\right]. \tag{3}$$

Satisfaction constraints: Apart from protecting the environment and increasing total social revenue, the colliery production plan can have a significant impact on the local authority's behavior. Therefore, the site selection decision needs to ensure a certain colliery satisfaction degree. Depending on the coal gangue stack allowance, the colliery requires a greater transportation capacity, but the the local authority's CGF site selection means that the transportation capacity is fixed. However, as the transportation capacity is closely related to the colliery satisfaction degree, the local authority defines the location satisfaction degree for each colliery using the following [43]:

$$g_j(X_i) = \begin{cases} 0, & \sum_{i=1}^{I} X_i T_{ij}^{cg} + \alpha E\left[\widetilde{E_j^g}\right] H_j < E\left[\widetilde{E_j^g}\right] Y_j^{basic} \\ \frac{\sum_{i=1}^{I} X_i T_{ij}^{cg} + \alpha E\left[\widetilde{E_j^g}\right] H_j - E\left[\widetilde{E_j^g}\right] Y_j^{basic}}{E\left[\widetilde{E_j^g}\right]\left(Y_j^{capacity} - Y_j^{basic}\right)}, & E\left[\widetilde{E_j^g}\right] Y_j^{basic} < \sum_{i=1}^{I} X_i T_{ij}^{cg} + \alpha E\left[\widetilde{E_j^g}\right] H_j < E\left[\widetilde{E_j^g}\right] Y_j^{capacity} \\ 1, & \sum_{i=1}^{I} X_i T_{ij}^{cg} + \alpha E\left[\widetilde{E_j^g}\right] H_j > E\left[\widetilde{E_j^g}\right] Y_j^{capacity}. \end{cases} \tag{4}$$

This function means that there is a basic output ($E\left[\widetilde{E_j^g}\right] Y_j^{basic}$) and a capacity output ($E\left[\widetilde{E_j^g}\right] Y_j^{capacity}$) for the coal gangue at each colliery. If $\sum_{i=1}^{I} X_i T_{ij}^{cg} + \alpha E\left[\widetilde{E_j^g}\right] H_j$ is less than $E\left[\widetilde{E_j^g}\right] Y_j^{basic}$, the satisfaction degree is zero; if $\sum_{i=1}^{I} X_i T_{ij}^{cg} + \alpha E\left[\widetilde{E_j^g}\right] H_j$ is more than $E\left[\widetilde{E_j^g}\right] Y_j^{capacity}$, the satisfaction degree is one. To ensure that the policy is successful, the local authority needs to ensure that the satisfaction degree at each colliery is not less than β, which can be expressed as follows:

$$\min\left(g_j(X_i)\right) \geq \beta. \tag{5}$$

Factory limitations: Considering the construction costs and efficiency, the local authority can select only one site from the total alternative sites to build the CGF.

$$\sum_{i=1}^{I} x_i = 1. \tag{6}$$

Colliery coal production and gangue transportation plan: As the main coal gangue producer, the colliery owner seeks to maximize profits. Therefore, efficient production and transportation plans are essential.

Profits maximization: The local authority site selection strategy restrains colliery behavior; however, colliery plans impact the local authority's achievement of its own objectives to minimize the total coal gangue stacks and maximize the total social revenue. Each colliery, therefore, requires an optimal production and transportation plan to maximize profits.

As a scarce resource, coal supply is generally less than demand. Colliery revenue, therefore, depends mainly on the coal output, which is expressed as $Y_j P_j^c$.

Total costs are made up of operating costs, taxes and coal gangue-related costs; operating costs are expressed as $Y_j \widetilde{C_j^o}$, and taxes are expressed as $\psi P_j^c Y_j$. The coal gangue-related costs are transportation costs and excess stack costs. Each colliery's coal gangue transportation quantity is decided by the colliery; i.e., R_{ij}, with the transportation costs at each colliery expressed as $\left(\sum_{i=1}^{I} X_i R_{ij}\right) \widetilde{C_j^t}$. The excess stack cost is determined by the stack quantity, the allowed stack level and the allowed excess stack level, i.e., $\left(\left(E\left[\widetilde{E_j^g}\right] Y_j - \sum_{i=1}^{I} X_i R(ij)\right) - \alpha H_j\right) P_s$. Similar to parameter $\widetilde{E_j^g}$, the variable costs (i.e., $\widetilde{C_j^o}, \widetilde{C_j^t}$) of the CGF-SS system are also triangular fuzzy numbers. That is, $\widetilde{C_j^o} = (b_{1j}, b_{2j}, b_{3j})$, $\widetilde{C_j^t} = (c_{1j}, c_{2j}, c_{3j})$ and

$b[.], c[.]$ are the respective membership function parameters for the above triangular fuzzy numbers. Using the fuzzy measure Me, the fuzzy variables $\widetilde{C_j^o}$ and $\widetilde{C_j^t}$ can be transformed into crisp forms $E\left[\widetilde{C_j^o}\right], E\left[\widetilde{C_j^t}\right]$; therefore, the total profits at colliery j are established as:

$$\max_{Y_j} F_j = Y_j P_j^c - E\left[\widetilde{C_j^o}\right] Y_j - \psi P_j^c Y_j - E\left[\widetilde{C_j^t}\right]\left(\sum_{i=1}^{I} X_i d_{ij} R_{ij}\right) - \left(\left(E\left[\widetilde{E_j^g}\right] Y_j - \sum_{i=1}^{I} X_i R(ij)\right) - \alpha H_j\right) P_s. \quad (7)$$

Basic production and capacity limitations: As the CGF project investment cycle is long, there are many fixed costs for each colliery in the construction process, even when the output is zero; hence, the collieries need to maintain a certain basic output. In other words, the coal output cannot be less than a basic line, C_j^{basic}. Further, based on the economic development plan and the productivity restrictions, coal output cannot be greater than the capacity, $C_j^{capacity}$.

$$C_j^{basic} < Y_j \leq C_j^{capacity}. \quad (8)$$

Cost budget constraints: In the CGF site selection problem, total costs are strictly controlled by the colliery decision makers and cannot be more than the allocated budget, C_m.

$$E\left[\widetilde{C_j^o}\right] Y_j + E\left[\widetilde{C_j^t}\right]\left(\sum_{i=1}^{I} X_i d_{ij} R_{ij}\right) \leq C_j^m. \quad (9)$$

Stack quantity constraints: Even if the local authority allows coal gangue piles at the colliery, there is a stack level limitation α, which is set by the local authority based on historical data H_j. Meanwhile, the allowed excess stack level φ is also set to avoid unrecoverable effects on the environment. Hence, under these restrictions, the collieries cannot generate additional coal gangue:

$$E\left[\widetilde{E_j^g}\right] Y_j - \sum_{i=1}^{I} X_i R_{ij} \leq (\alpha + \varphi) H_j. \quad (10)$$

Basic demand constraint: One of the main targets for the local authority is to maintain a stable and sustainable development of the coal fields; therefore, all of the collieries' coal outputs should be more than the basic market demand, D^{basic}.

$$\sum_{j=1}^{J} Y_i \geq D^{basic}. \quad (11)$$

Transportation quantity constraint: Under the local authority, each colliery attempts to transport as great a coal gangue quantity as possible to the CGF. However, the transportation quantity is limited by the coal production plan. In other words, the total coal gangue transportation quantity at each colliery cannot be more than the production quantity, $E\left[\widetilde{E_j^g}\right] Y_j$.

$$\sum_{i=1}^{I} X_i R_{ij} \leq E\left[\widetilde{E_j^g}\right] Y_j. \quad (12)$$

Transportation capacity constraint: The transportation quantity is limited by transportation capacity. In other words, the transportation quantity decision, R_{ij}, cannot be more than the transportation capacity, T_{ij}^{cg}.

$$R_{ij} \leq T_{ij}^{cg}. \quad (13)$$

Global model for CGF site selection: To mitigate coal gangue contamination, the local authority plans to establish a coal gangue recycling facility, for which CGF site selection is particularly important. The government is responsible for the selection of the CGF site, but is constrained by the site decision, local policies and the coal output and gangue transportation plan from each colliery. When selecting a CGF site, the local authority first ensures the collieries' satisfaction degree and then seeks to minimize the total coal gangue stacks, as expressed in Equation (2). The site selection decision should also maximize total social revenue, as expressed in Equation (3), which is dependent on the collieries' decisions. To achieve profit maximization, as expressed in Equation (7), colliery owners decide on the coal output and gangue transportation plan based on the selected CGF site. Because there are unavoidable conflicts within the CGF-SS system, it can be described as a typical Stackelberg game between the local authority and collieries. In this situation, it is too difficult to describe the complex inherent relationship using a simple site selection model. Therefore, based on Equations (1)–(13), a bi-level model is formulated to deal with these conflicts, as follows:

$$
\begin{aligned}
&\min_{X_i} Z_1 = \sum_{j=1}^{J} \left(E\left[\widetilde{E_j^g}\right] Y_j - \sum_{i=1}^{I} X_i R(ij) \right) \\
&\max_{X_i} Z_2 = \sum_{j=1}^{J} \left[\psi P_j^c Y_j + \vartheta \sum_{i=1}^{I} X_i R_{ij} + \left(\left(E\left[\widetilde{E_j^g}\right] Y_j - \sum_{i=1}^{I} X_i R(ij) \right) - \alpha H_j \right) P_s \right] \\
&\text{s.t.} \left\{
\begin{array}{l}
\min \left(g_j(X_i) \right) \geq \beta \\
\sum_{i=1}^{I} X_i = 1 \\
X_i = 0 \text{ or } 1 \\
\forall i = 1, 2, \ldots, I \\
\forall j = 1, 2, \ldots, J \\
\max_{Y_j, R_{ij}} F_j = Y_j P_j^c - E\left[\widetilde{C_j^o}\right] Y_j - \psi P_j^c Y_j - E\left[\widetilde{C_j^t}\right] \left(\sum_{i=1}^{I} X_i d_{ij} R_{ij} \right) - \left(\left(E\left[\widetilde{E_j^g}\right] Y_j - \sum_{i=1}^{I} X_i R(ij) \right) - \alpha H_j \right) P_s \\
\text{s.t.} \left\{
\begin{array}{l}
C_j^{basic} < Y_j \leq C_j^{capacity} \\
E\left[\widetilde{C_j^o}\right] Y_j + E\left[\widetilde{C_j^t}\right] \left(\sum_{i=1}^{I} X_i d_{ij} R_{ij} \right) \leq C_j^m \\
E\left[\widetilde{E_j^g}\right] Y_j - \sum_{i=1}^{I} X_i R_{ij} \leq (\alpha + \varphi) H_j \\
\sum_{j=1}^{J} Y_i \geq D^{basic} \\
\sum_{i=1}^{I} X_i R_{ij} \leq E\left[\widetilde{E_j^g}\right] Y_j \\
R_{ij} \leq T_{ij}^{cg} \\
\forall i = 1, 2, \ldots, I \\
\forall j = 1, 2, \ldots, J.
\end{array}
\right.
\end{array}
\right.
\end{aligned}
\tag{14}
$$

In consideration of the conflict between the local authority and the colliery objectives, the model in Equation (14) is proposed for optimal CGF site selection, within which the local authority considers each colliery's satisfaction degree. The model in Equation (14) can also be applied to an analogical situation when adding, reducing or altering the objective functions or constraints. For example, if the government prioritizes gangue stack reduction without considering social revenue, then the objective function in Equation (14) focuses only on total coal gangue stack minimization; if the colliery wished to prioritize the trade-off between increased profits and total costs, the cost budget constraint should be removed. In this model, parameter β expresses the colliery cooperation degree to the CGF-SS policy, and parameter α indicates the local authority's lowest limits for the gangue stacks. Intuitively, the Stackelberg-equilibrium model established in Equation (14) is effectively describing the CGF-SS problem.

3.3. Model Transformation and Solution Approach

3.3.1. Model Transformation

The proposed model in Equation (14) is a multi-objective bi-level decision making problem. However, there are many difficulties in multiple objective problems because the dimensionality of each objective function is generally different. Under the circumstances, the multiple objectives are integrated to a single objective using a weighted-sum method. Let $Z_1^{'}$ and $Z_2^{'}$ be the same order of magnitude: $Z_1^{'} = Z_1/Z_1^{min}$ and $Z_2^{'} = Z_2^{max}/Z_2$, where Z_1^{min} denotes the minimum value of Z_1 and Z_2^{max} denotes the maximum value of Z_2, when only the one objective is considered in this study. Then, the integrated value using the weight-sum method is calculated as: $MIV = w_1Z_1^{'} + w_2Z_2^{'}$. Based on this weight coefficient, the multiple objectives can be converted to a single objective, i.e., $\max_{X_i} MIV = w_1Z_1^{'} + w_2Z_2^{'}$.

In addition, it is also particularly difficult to handle the bi-level programming model because it is an NP-hard problem [44]. Research on bi-level programming problems has found that the KKT approach is an efficient method for converting the bi-level problem into a single-level problem [45]. The core theory for the KKT approach is that the game between the upper level and the lower level is reduced to a single decision making problem by constraining the upper level using the KKT conditions [46]. Therefore, based on previous work by Shi et al. [47] and Equation (14), the bi-level multi-objective model is transformed into an equivalent crisp model, as follows:

$$
\begin{aligned}
&\max_{X_i} MIV = w_1Z_1^{'} + w_2Z_2^{'} \\
&s.t.\left\{
\begin{array}{l}
\sum\limits_{j=1}^{J}\left(E\left[\widetilde{E_j^g}\right]Y_j - \sum\limits_{i=1}^{I}X_iR_{ij}\right) \le \gamma\sum\limits_{j=1}^{J}H_j \\
\min\left(g_j(X_i)\right) \ge \beta \\
\sum\limits_{i=1}^{I}X_i = 1 \\
X_i = 0 \text{ or } 1 \\
C_j^{basic} < Y_j \le C_j^{capacity} \\
E\left[\widetilde{C_j^o}\right]Y_j + E\left[\widetilde{C_j^t}\right]\left(\sum\limits_{i=1}^{I}X_iR_{ij}\right) \le C_j^m \\
E\left[\widetilde{E_j^g}\right]Y_j - \sum\limits_{i=1}^{I}X_iR_{ij} \le (\alpha+\varphi)H_j \\
\sum\limits_{j=1}^{J}Y_i \ge D^{basic} \\
\sum\limits_{i=1}^{I}X_iR_{ij} \le E\left[\widetilde{E_j^g}\right]Y_j \\
R_{ij} \le T_{ij}^{cg} \\
(1-v_3)E\left[\widetilde{C_j^t}\right]\sum\limits_{i=1}^{I}X_id_{ij} + \sum\limits_{i=1}^{I}X_iP_s + v_4 - v_6 - v_7 = 0 \\
(1-\psi)P_j^c + E\left[\widetilde{E_j^g}\right]P_s - v_1 + v_2 - (1+v_3)E\left[\widetilde{C_j^o}\right] + v_5 + (v_6-v_4)E\left[\widetilde{E_j^g}\right] = 0 \\
v_1f_1(X_i,Y_j,R_{ij}) + v_2f_2(X_i,Y_j,R_{ij}) + v_3f_3(X_i,Y_j,R_{ij}) + v_4f_4(X_i,Y_j,R_{ij}) \\
+v_5f_5(X_i,Y_j,R_{ij}) + v_6f_6(X_i,Y_j,R_{ij}) + v_7f_7(X_i,Y_j,R_{ij}) = 0 \\
f_1(X_i,Y_j,R_{ij}) = C_j^{capacity} - Y_j \ge 0 \\
f_2(X_i,Y_j,R_{ij}) = Y_j - C_j^{basic} \ge 0 \\
f_3(X_i,Y_j,R_{ij}) = C_j^m - E\left[\widetilde{C_j^o}\right]Y_j - E\left[\widetilde{C_j^t}\right]\left(\sum\limits_{i=1}^{I}X_id_{ij}R_{ij}\right) \ge 0 \\
f_4(X_i,Y_j,R_{ij}) = (\alpha+\varphi)H_j - E\left[\widetilde{E_j^g}\right]Y_j + \sum\limits_{i=1}^{I}X_iR_{ij} \ge 0 \\
f_5(X_i,Y_j,R_{ij}) = \sum\limits_{j=1}^{J}Y_i - D^{basic} \ge 0 \\
f_6(X_i,Y_j,R_{ij}) = E\left[\widetilde{E_j^g}\right]Y_j - \sum\limits_{i=1}^{I}X_iR_{ij} \ge 0 \\
f_7(X_i,Y_j,R_{ij}) = T_{ij}^{cg} - R_{ij} \ge 0 \\
v_t \ge 0;\ t = 1,2,\ldots,7. \\
\forall i = 1,2,\ldots,I; \forall j = 1,2,\ldots,J.
\end{array}
\right.
\end{aligned}
\tag{15}
$$

In the objective conversion process, the weighted-sum method allows the government to realize the environment protection target and to achieve social revenue maximization. In the KKT transformation, each local authority decision corresponds to an optimal colliery behavior. Therefore, the complex inherent conflicts between the government and colliery owner are integrated in the KKT conditions, which changes the CGF site selection problem from a game between the local authority and colliery to a single decision making problem by the local authority. Though a single level programming with only one objective is also complicated, it can be solved using the existing algorithms [47].

3.3.2. Solution Approach

Based on the proposed integrated method, the solution approach for CGF location problem includes the following two parts (as shown in Figure 4). First, this paper identifies the alternative CGF sites by GIS; then, based on the identification results, the optimal CGF site is obtained by running the model (as show in Equation (16)) on the software MATLAB 2007 (MATLAB R2007b; Mathworks: Natick, MA, USA). In addition, the detail procedures of this solution for the single-level single-objective model can be abstracted as follows:

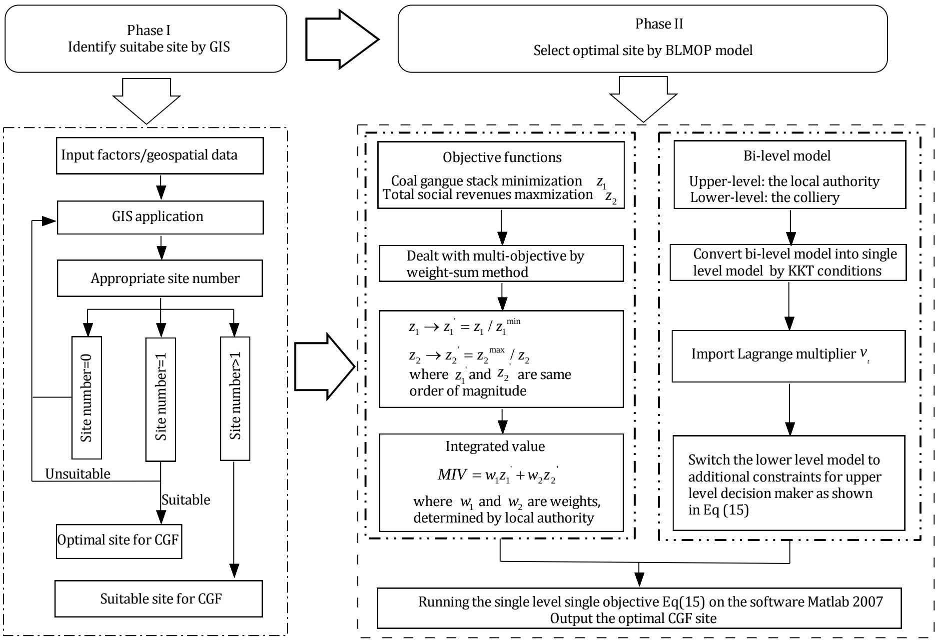

Figure 4. Overall flowchart for the solution approach.

Step 1: Build the feasible region for the single-level single-objective model.
Step 2: Set $i = 1$.
Step 3: Initialize $x_i = 1$.
Step 4: Set $n = 1$.
Step 5: Generate a vector of v_t randomly with zero or one; obtain $\min Z_1 = \sum_{j=1}^{J}\left(E\left[\widetilde{E_j^g}\right]Y_j - \sum_{i=1}^{I} X_i R(ij)\right)$ and $\max Z_2 = \sum_{j=1}^{J}\left[\psi P_j^c Y_j + \vartheta \sum_{i=1}^{I} X_i R_{ij} + \left(\left(E\left[\widetilde{E_j^g}\right]Y_j - \sum_{i=1}^{I} X_i R(ij)\right) - \alpha H_j\right) P_s\right]$; and then, calculate MIV = $w_1 Z_1' + w_2 Z_2'$.
Step 6: If $n < N$, let $n = n + 1$; return to Step 5; otherwise, MIV$_i$ = max MIV; go to Step 7.
Step 7: If $i < I$, let $i = i + 1$; return to Step 3; otherwise, stop the algorithm, and output the Pareto set.

4. Case Study

In this section, a case study for a practical CGF site identification and selection problem in the Yanzhou coal field in China is introduced to demonstrate the effectiveness of the proposed optimal methodology.

4.1. Case Region Presentation

The demand for coal has increased rapidly as populations have increased around the world, resulting in significant coal gangue plied in the coal field. According to the statistics, the total accumulative storage of coal gangue has reached 7.5 × 10^9 tons until 2013, and there are about 3000 gangue-related hills in China [1,2]. Optimal CGF site selection, therefore, has a significant influence on coal gangue contamination mitigation. Moreover, the geospatial data and the colliery need to be considered when the local authority makes site identification and selection decisions. To explore the applicability of the proposed method, the Yanzhou coal field is used as an application case.

Yanzhou coal field occupies 3400 square kilometers in the southwest of Shandong Province. The total coal reserves are estimated to be around 9.1 billion tonnes. The research region is shown in Figure 5. There are six major collieries in this area; the South Tuen colliery, the Xinglongzhuang colliery, the Baodian colliery, the Dongtan colliery, the Jining No. 2 colliery, the Jining No. 3 colliery (i.e., ST, South Tuen; XLZ, Xing longzhuang; BD, Baodian; DT, Dongtan; JN2, Jining No. 2; JN3, Jining No. 3). The locations for all collieries are also shown in Figure 5. Yanzhou coal field produces thermal coal, and the carbon in gangue is greater than 20%; hence, it can be used to generate electricity [48]. In other words, the local authority wishes to build a coal gangue power facility (CGPF) to achieve the coal gangue contamination reduction.

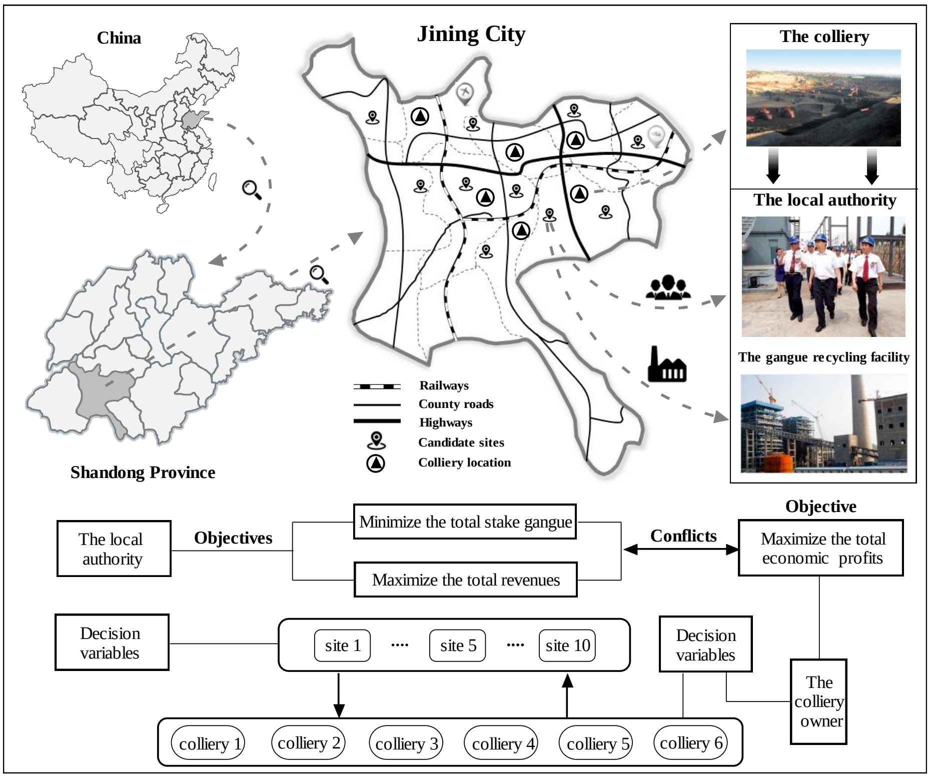

Figure 5. The geographical position of Yanzhou coal field.

4.2. GIS Technique for Identifying the Potential Candidate Site for the CGPF

The factors for a suitable CGPF location are determined from the geographical environment and the local regulations, with the related data being collected from the CGPF construction project. ArcGIS software is used to deal with the spatial data and to produce a CGPF map for the Yanzhou coal field. In practice, identifying the candidate sites is based on the available land located at a reasonable distance from other land uses. The reasonable distance in this paper is expressed as a buffer zone. Depending on the different features, the buffer zone characteristics are as follows; 0.25 km from electricity networks and vehicular roads, 1 km from farm pumps, water wells, residential areas, railways and paved roads and 5 km from pipelines and airports. The above assigned buffer zone dimensions are determined based on Argyriou et al. [49], and suitable and unsuitable areas are screened. Then, the suitable area is divided into 5 km × 7 km units using ArcGIS in ESRI. A global digital elevation model (GDEM) is used to analyze the topographic characteristics [50]; the GRID module in ARCInfo is used to determine slope information [51], and the location of the alternative sites is ensured using overlay analysis [52]. Ten candidate sites are finally identified, as shown in Figure 5.

4.3. Modeling Technique to Select the Most Appropriate CGPF Site

Because there are many conflicts between the government and each colliery owner, the modeling is used to select the most appropriate site for the CGPF construction project.

4.4. Data Collection for the Bi-Level Model

The six major collieries are considered in this case to ensure the efficiency of the results. Certain parameters, such as basic output, production capacity, sale price, historical output and budget, are obtained from the Statistical Yearbook of the Chinese coal industry [53] and information published by the companies, as shown in Table 1. Detailed data, such as the distance and transportation capacity between each colliery and the CGPF candidate site, are collected from field research before the application of the modeling, as shown in Tables 2 and 3. The uncertain parameters, gangue emission coefficient, unit operating costs and unit transportation costs are estimated from expert experience and are considered as fuzzy parameters, as shown in Table 4. To ensure project effectiveness, some coal field parameters are also needed, as shown in Table 5. The reduction target and basic coal demand are obtained from the Chinese Waste Recycling Technology Engineering Twelfth Five-Year Special Plan [54] and the Chinese Coal Industry Development Plan for the the Twelfth Five-Year Plan [55]. The economic revenue coefficient for a unit of gangue is obtained from an existing coal gangue power facility.

Table 1. Basic information for each colliery.

	Basic Output C_j^{basic} **(10^6 Tons)**	**Production Capacity** $C_j^{capacity}$ **(10^6 Tons)**	**Sale Price** P_j^c **(Yuan/Ton)**	**History Output** H_j **(10^6 Tons)**	**Cost Budget** C_j^m **(10^8 Yuan)**
ST	2.4	4	808	3.9	20
XLZ	3	7.5	776	6.9	46
BD	3	6.5	770	6.2	30
DT	4	9	798	8.1	53
JN2	4	6	810	4.4	29
JN3	5	7	773	6.5	32

Table 2. Distance between the colliery and the CGPF candidate site (km).

	Site 1	**Site 2**	**Site 3**	**Site 4**	**Site 5**	**Site 6**	**Site 7**	**Site 8**	**Site 9**	**Site 10**
ST	46	147	101	52	68	52	89	85	61	76
XLZ	72	62	85	97	98	55	111	95	94	148
BD	55	78	98	49	54	75	94	94	64	74
DT	98	94	64	152	49	69	67	76	130	83
JN2	62	126	88	71	152	42	82	82	109	119
JN3	90	66	76	68	132	53	90	67	80	78

Table 3. Transportation capacity between the colliery and the CGPF candidate site (10^6 tons).

	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Site 8	Site 9	Site 10
ST	0.2846	0.1139	0.1025	0.1175	0.0745	0.1185	0.1271	0.1402	0.2445	0.1334
XLZ	0.1584	0.2132	0.1826	0.0473	0.2466	0.2393	0.2328	0.1321	0.1651	0.1673
BD	0.2504	0.1667	0.1898	0.3219	0.1217	0.1362	0.2128	0.2128	0.3876	0.2513
DT	0.1634	0.2466	0.1656	0.1872	0.2535	0.2458	0.3653	0.1436	0.1105	0.3412
JN2	0.2188	0.2609	0.3629	0.4198	0.2575	0.2669	0.3811	0.1811	0.1363	0.0979
JN3	0.2919	0.1953	0.1514	0.1905	0.2135	0.2065	0.2383	0.0984	0.2607	0.2092

Table 4. Uncertainty parameters for each colliery.

	Gangue Emission Coefficient $\widetilde{E_j^g}$	Unit Operating Cost $\widetilde{C_j^o}$ (Yuan/Ton/km)	Unit Transportation Cost $\widetilde{C_j^t}$ (Yuan/Ton)
ST	(18.21%, 19.86%, 20.13%)	(221, 223, 225)	(56, 58, 60)
XLZ	(13.71%, 16.35%, 18.29%)	(199, 207, 214)	(49, 52, 55)
BD	(15.36%, 18.07%, 19.74%)	(211, 219, 232)	(53, 55, 58)
DT	(12.92%, 15.03%, 16.08%)	(208, 220, 224)	(52, 56, 57)
JN2	(15.74%, 18.62%, 19.91%)	(207, 218, 227)	(51, 54, 57)
JN3	(16.12%, 17.49%, 19.25%)	(198, 213, 226)	(50, 53, 56)

Table 5. Input parameters in the CGPF site selection system.

α	ϑ (Yuan/Ton)	D^{basic} (10^6 Tonnes)	Tax Rate	P_s (Yuan/Ton)
60%	280	28	20%	116

4.5. Computational Results under Different Situations

After transformation using the weighted-sum method and KKT conditions, the single-level programming with only one objective is run on the MATLAB 2007, and the results are calculated when $\theta_1 = 0.5$ and $\theta_2 = 0.5$, where $\theta_1 + \theta_2 = 1$. In practice, some subjective parameters determined by the local authority significantly influence colliery owner behavior. Consequently, to ensure the efficiency of the proposed model, the allowed excess stack level φ and satisfaction degree β are considered in the following scenarios. When the allowed excess stack level is 40%, this indicates that the local authority has a relaxed policy for coal gangue contamination and that the coal gangue stack quantity at each colliery can be up to the previous year with paying for the expensive stack costs. Moreover, it is essential for each colliery to make decisions to balance the transportation costs and stack costs. Based on the different satisfaction degrees, the integrated value for each candidate site is calculated, as shown in Table 6. From Table 6, it can be seen that the optimal site decided by the government does not change with the different satisfaction degree β. When the government sets a fixed β with a changing φ, Site 6 is also seen to be the most suitable site for the CGPF, as it ranks first for the integrated value (see Tables 7–9). In addition, when the allowed excess stack level φ is changed under different basic satisfaction degrees, the coal production plan and gangue transportation plan for each colliery are shown in Figures 6–8.

Table 6. Results of BLMOP model with different satisfaction degrees when the allowed excess stack level φ is 40% (10^8 RMB).

β		Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Site 8	Site 9	Site 10
0.7	MIV	0.8403	0.9191	0.8189	0.8952	0.9232	**0.9287**	0.8820	0.9019	0.8695	0.8672
	Rankings	Site 6 > Site 5 > Site 2 > Site 8 > Site 4 > Site 7 > Site 9 > Site 10 > Site 1 > Site 3									
0.8	MIV	0.8304	0.8854	0.8042	0.8609	* * *	**0.9349**	0.8750	0.8859	0.8626	0.8485
	Rankings	Site 6 > Site 8 > Site 2 > Site 7 > Site 9 > Site 4> Site 10 > Site 1 > Site 3									
0.9	MIV	0.8426	* * *	0.8165	0.8747	* * *	**0.9237**	0.8647	0.8871	0.8529	0.8688
	Rankings	Site 6 > Site 8 > Site 4 > Site 10> Site 7 > Site 9 > Site 1 > Site 3									

Notes: the highlighted figures in the table are the maximum MIV in each line.

Table 7. Results of BLMOP model with different excess stack levels when $\beta = 0.7$ (10^8 RMB).

φ		Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Site 8	Site 9	Site 10
30%	MIV	0.8910	0.9075	0.8735	0.8838	0.9156	**0.9280**	0.8613	0.8778	0.8486	0.8443
	Rankings	Site 6 > Site 5 > Site 2 > Site 1 > Site 4 > Site 8 > Site 3 > Site 7 > Site 9 > site 10									
20%	MIV	0.8865	0.9028	0.8691	0.8793	0.9109	**0.9227**	0.8571	0.8734	0.8380	0.8402
	Rankings	Site 6 > Site 5 > Site 2 > Site 1 > Site 4 > Site 8 > Site 3 > Site 7 > Site 10 > Site 9									
10%	MIV	0.8991	0.8974	0.8814	0.8918	0.9242	**0.9510**	0.8689	0.8872	0.8495	0.8516
	Rankings	Site 6 > Site 5 > Site 1 > Site 2 > Site 4 > Site 8 > Site 3 > Site 7 > Site 10 > Site 9									
0%	MIV	0.8981	0.9500	0.8778	0.9148	0.9584	**0.9662**	0.8478	0.8666	0.8420	0.8371
	Rankings	Site 6 > Site 5 > Site 2 > Site 4 > Site 1 > Site 3 > Site 8 > Site 7 > Site 9 > Site 10									

Notes: the highlighted figures in the table are the maximum MIV in each line.

Table 8. Results of BLMOP model with different excess stack levels when $\beta = 0.8$ (10^8 RMB).

φ		Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Site 8	Site 9	Site 10
30%	MIV	0.8869	0.9262	0.8641	0.9226	* * *	**0.9393**	0.8937	0.9223	0.9007	0.8836
	Rankings	Site 6 > Site 2 > Site 8 > Site 4> Site 9 > Site 10 > Site 1 > Site 3									
20%	MIV	0.8798	0.9189	0.8572	0.9153	* * *	**0.9486**	0.8866	0.9150	0.8935	0.8765
	Rankings	Site 6 > Site 2 > Site 4 > Site 8 > Site 9 > Site 7 > Site 1 > Site 10 > Site 3									
10%	MIV	0.8530	0.9139	0.8369	0.9051	* * *	**0.9432**	0.8891	0.9122	0.8818	0.8713
	Rankings	Site 6 > Site 2 > Site 8 > Site 4 > Site 7 > Site 9 > Site 10 > Site 1 > Site 3									
0%	MIV	0.8794	0.9217	0.8631	0.9339	* * *	**0.9378**	0.9173	0.9299	0.8936	0.8832
	Rankings	Site 6 > Site 8 > Site 4 > Site 2 > Site 7 > Site 9 > Site 10 > Site 1 > Site 3									

Notes: the highlighted figures in the table are the maximum MIV in each line.

Table 9. Results of BLMOP model with different excess stack levels when $\beta = 0.9$ (10^8 RMB).

φ		Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Site 8	Site 9	Site 10
30%	MIV	0.8385	* * *	0.8197	0.9054	* * *	**0.9234**	0.8809	0.9027	0.8671	0.8528
	Rankings	Site 6 > Site 4 > Site 8 > Site 7 > Site 9 > Site 10 > Site 1 > Site 3									
20%	MIV	0.8240	* * *	0.8057	0.8895	* * *	**0.9479**	0.8659	0.8875	0.8412	0.8423
	Rankings	Site 6 > Site 4 > Site 8 > Site 7 > Site 10 > Site 9 > Site 1 > Site 3									
10%	MIV	0.8358	* * *	0.8172	0.8888	* * *	**0.9609**	0.8809	0.9003	0.8533	0.8544
	Rankings	Site 6 > Site8 > Site 4 > Site 7 > Site 10 > Site 9 > Site 1 > Site 3									
0%	MIV	0.8650	* * *	0.9116	0.9197	* * *	**0.9581**	0.8457	0.9316	0.8912	0.8798
	Rankings	Site 6 > Site8 > Site 4 > Site 3 > Site 9 > Site 10 > Site 1 > Site 7									

Notes: the highlighted figures in the table are the maximum MIV in each line.

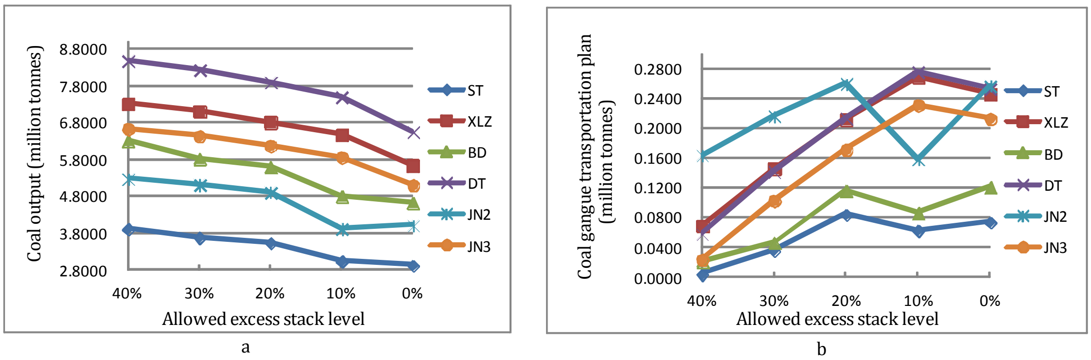

Figure 6. Reaction of each colliery when the minimum satisfaction degree is 0.7. (**a**) The coal output plan for each colliery with the excess stack level changing when $\beta = 0.7$; (**b**) The coal gangue transportation plan for each colliery with the excess stack level changing when $\beta = 0.7$.

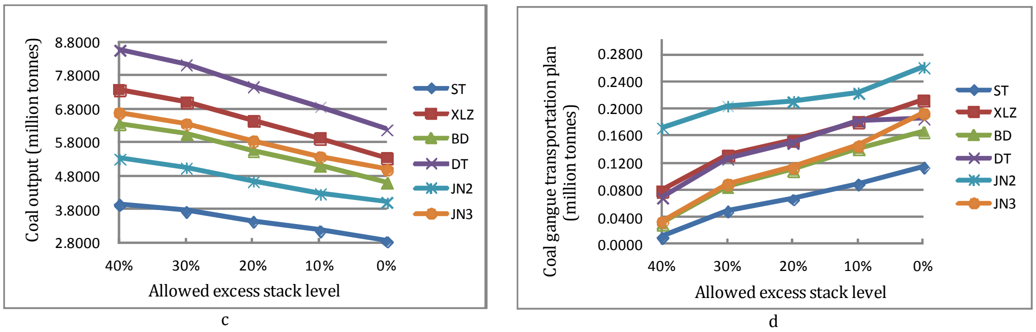

Figure 7. Reaction of each colliery when the minimum satisfaction degree is 0.8. (**c**) The coal output plan for each colliery with the excess stack level changing when $\beta = 0.8$; (**d**) The coal gangue transportation plan for each colliery with the excess stack level changing when $\beta = 0.8$.

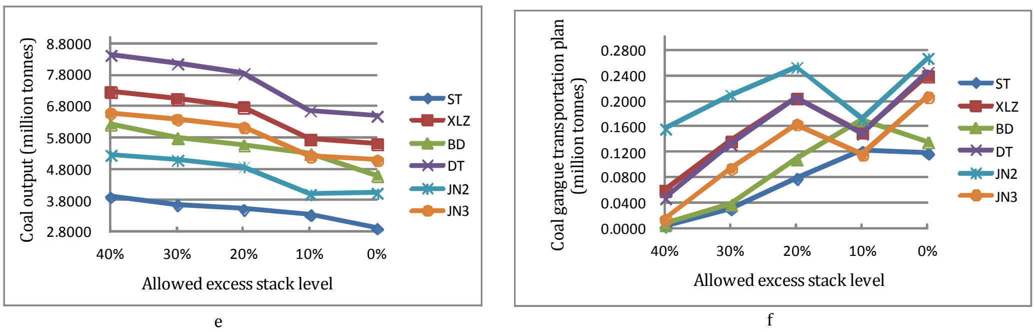

Figure 8. Reaction of each colliery when the minimum satisfaction degree is 0.9. (**e**) The coal output plan for each colliery with the excess stack level changing when $\beta = 0.9$; (**f**) The coal gangue transportation plan for each colliery with the excess stack level changing when $\beta = 0.9$.

4.6. Sensitivity Analysis on the Weights

The above results are obtained using certain weights (e.g., $w_1 = w_2 = 0.5$); however, the preference for the local government is not considered. Thus, the results may change with different weights. To check the robustness of the computational results, this paper uses a sensitivity analysis on the weights to demonstrate the impacts on the rankings of the alternatives. Considering the government's preference, five combinations of w_1 and w_2 are selected ranging between 0.2 and 0.8, where the gap between each combination is 0.15. The results for the five situations are illustrated in Table 10, while the satisfaction degree β is 0.8, and the allowed excess stack level φ is 20%. Figure 9 graphically shows the analysis results. It can be found that final MIV values are effected by the changing weights; however, Site 6 is still the optimal site for both the government and the colliery owner. As a result, the developed method is demonstrated to be robust when there are small perturbations in the changing weights.

Table 10. Results of BLMOP model with different weights when $\beta = 0.8$, $\varphi = 20\%$ (10^8 RMB).

Candidates		**Site 1**	**Site 2**	**Site 3**	**Site 4**	**Site 5**	**Site 6**	**Site 7**	**Site 8**	**Site 9**	**Site 10**
Candidate 1											
$w_1 = 0.8$	MIV	0.8732	0.8673	0.8541	0.8873	* * *	**0.9364**	0.9121	0.8906	0.8602	0.9017
$w_2 = 0.2$	Rankings	Site 6 > Site 7 > Site 10 > Site 8 > Site 4 > Site 1 > Site 2 > Site 9> Site 3									
Candidate 2											
$w_1 = 0.65$	MIV	0.8765	0.8791	0.8567	0.8991	* * *	**0.9419**	0.8987	0.9006	0.8623	0.8902
$w_2 = 0.35$	Rankings	Site 6 > Site 8 > Site 4 > Site 7 > Site 10 > Site 2 > Site 1 > Site 9 > Site 3									
Candidate 3											
$w_1 = 0.5$	MIV	0.8798	0.9189	0.8572	0.9153	* * *	**0.9486**	0.8866	0.9150	0.8935	0.8765
$w_2 = 0.5$	Rankings	Site 6 > Site2 > Site4 > Site 8 > Site 9 > Site 7 > Site 1 > Site 10 > Site 3									
Candidate 4											
$w_1 = 0.35$	MIV	0.9025	0.9218	0.8737	0.8953	* * *	**0.9425**	0.8727	0.8991	0.8811	0.8753
$w_2 = 0.65$	Rankings	Site 6 > Site 2 > Site 1 > Site 8 > Site 4 > Site 9 > Site 10 > Site 3 > Site 7									
Candidate 5											
$w_1 = 0.2$	MIV	0.9154	0.9317	0.8919	0.8858	* * *	**0.9418**	0.8633	0.8874	0.8773	0.8674
$w_2 = 0.8$	Rankings	Site 6 > Site2 > Site 1 > Site 3 > Site 8 > Site 4 > Site 9 > Site 10> Site 7									

Notes:the highlighted figures in the table are the maximum MIV in each line.

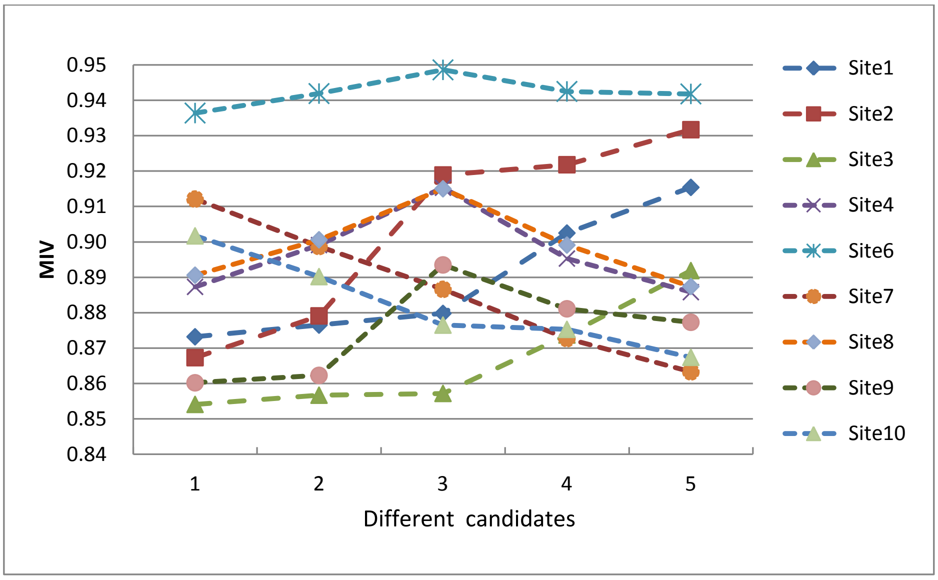

Figure 9. Site rankings from a sensitivity analysis with different weights.

4.7. Comparing Bi-Level CGF-SS with Single-Level CGF-SS

The traditional site selection problem in CGF construction projects is often carried out using a single-level model, which only considers the objectives of the local authority in the upper level and seldom includes the objectives of the colliery in the lower level. According to the theory of the single-level model proposed by Avittathur et al. [27], this paper formulates a single-level multi-objective programming model to select the optimal CGF site, as follows:

$$
\begin{aligned}
&\min_{X_i,Y_j,R_{ij}} Z_1 = \sum_{j=1}^{J}\left(E\left[\widetilde{E_j^g}\right]Y_j - \sum_{i=1}^{I} X_i R(ij)\right)\\
&\max_{X_i,Y_j,R_{ij}} Z_2 = \sum_{j=1}^{J}\left[\psi P_j^c Y_j + \vartheta \sum_{i=1}^{I} X_i R_{ij} + \left(\left(E\left[\widetilde{E_j^g}\right]Y_j - \sum_{i=1}^{I} X_i R(ij)\right) - \alpha H_j\right)P_s\right]\\
&s.t.\begin{cases}
\min\left(g_j(X_i)\right) \geq \beta\\
\sum_{i=1}^{I} X_i = 1\\
X_i = 0 \text{ or } 1\\
C_j^{basic} < Y_j \leq C_j^{capacity}\\
E\left[\widetilde{C_j^o}\right]Y_j + E\left[\widetilde{C_j^t}\right]\left(\sum_{i=1}^{I} X_i d_{ij} R_{ij}\right) \leq C_j^m\\
E\left[\widetilde{E_j^g}\right]Y_j - \sum_{i=1}^{I} X_i R_{ij} \leq (\alpha+\varphi)H_j\\
\sum_{j=1}^{J} Y_i \geq D^{basic}\\
\sum_{i=1}^{I} X_i R_{ij} \leq E\left[\widetilde{E_j^g}\right]Y_j\\
R_{ij} \leq T_{ij}^{cg}\\
\forall i = 1,2,\ldots,I\\
\forall j = 1,2,\ldots,J.
\end{cases}
\end{aligned}
\tag{16}
$$

To ensure the comparison equity, this paper first switches multiple objectives to a single objective using the weight-sum method and then runs the model on MATLAB 2007. The results for the two models with the same CGPF site selection case are shown in Table 11. Compared with the bi-level model, a lower coal gangue stack quantity and a higher social revenue are obtained by the single-level model. In the meantime, higher coal gangue transportation quantities explain why the coal gangue stack quantity doe not change considerable, although the coal output increases 8.41%. The revenue in the CGF is a part of the total social revenues; thus, the local authority allocates larger transportation capacity to the colliery with higher production capacity. Therefore, without considering the transportation costs, Site 7 is selected as the optimal CGPF site in the single-level model, because this decision enables the collieries with higher production capacity, such as XLZ colliery, DT colliery and JN3 colliery, to obtain larger transportation capacity. However, it ignores the colliery's benign development. The collieries with lower production capacity, especially ST colliery, can just ensure the basic demand because of limited transportation capacity. The bi-level model promotes the sustainable development of collieries by importing the game between the local authority and the colliery owner. Thus, it is more reasonable to use the proposed bi-level model in the real situation. Overall, using the bi-level model to select the CGF site is more suitable.

Table 11. Comparison between the bi-level model and the single-level model.

Problem	Total Coal Gangue Stack Quantity (10^6 Tons)	Total Social Revenues (10^8 Yuan)	Optimal Site	Total Coal Output (10^6 Tons)	Total Coal Gangue Transportation Quantity (10^6 Tons)
Bi-level	4.0156	57.0395	Site 6	28.9683	1.1674
Single-level	4.0149	59.2518	Site 7	31.4058	1.5569

5. Discussions

The above results indicate that a coal gangue facility can play an important role in reducing gangue contamination and that efficient CGF site identification and selection is vital. Based on the results under different situations, we formulate several propositions and identify some policy implications.

5.1. Propositions

Proposition 1. *The coal gangue contamination reduction-based facility recycling mechanism promotes environmental improvement.*

To protect environment around the coal field, a coal gangue facility recycling mechanism can be established by the proposed BLMOP model. When it is tested using the proposed GIS-modeling method, the decisions made by each colliery indicate that they all attempt to adjust the coal production plan and the coal gangue transportation plan to realize the equilibrium between stack costs and transportation costs (see Figures 6–8). Under the limited stack level, each colliery transports more coal gangue to the CGF to negotiate for a larger transportation capacity, even if it has a smaller unit revenue. Meanwhile, although the revenue of unit coal production is higher, the colliery owner still has to control coal output to avoid paying for huge stack costs (see Figures 6–8). In this situation, the coal gangue stack reduction target, which is pursued by the government, is achieved. As a consequence, this demonstrates that the facility recycling mechanism is conducive to mitigating coal gangue contamination, thereby promoting environmental improvement. Even though these results are obtained from the case in Yanzhou coal fields, similar conclusions can be drawn when this approach is used in other coal fields with some parameter changes. It is obvious that the colliery will transport as much coal gangue as possible to the CGF and control coal output under the facility recycling mechanism for sustainable development.

Proposition 2. *The allowed excess stack level has huge impacts on the total coal gangue recycling quantity.*

Table 12 shows that when the allowed excess stack level is 40% and the basic satisfaction degree is 0.7, the total coal gangue transportation quantity is 0.3440 million tonnes; when the allowed excess stack level is 0% with the similar β, the total coal gangue transportation quantity is 1.1674 million tonnes, which increases about 3.39-times compared to φ = 40%. When β = 0.8 and β = 0.9, the total coal gangue transportation quantity gap between φ = 40% and φ = 0% is 0.7384 million tonnes and 0.9216 million tonnes, which increase about 2.87-times and 4.86-times, respectively. Moreover, Table 12 also indicates that when the allowed excess stack level is too low or too high, the basic satisfaction degree almost has few impacts on the total gangue transportation quantity. Even though the total coal gangue transportation quantity fluctuates when β changes from 0.9 to 0.7, the change margin of the total coal gangue transportation quantity in the satisfaction degree is largely lower than in the allowed excess stack level. Therefore, it can be summarized that the total coal gangue transportation quantity is mainly influenced by the allowed excess stack level. Equation (10) indicates that the coal gangue transportation quantity is determined by the coal output and the allowed excess stack level. In reality, the colliery always keeps the relatively stable coal output to obtain more profits. The above analysis demonstrates that the total coal gangue transportation quantity is mainly determined by the allowed excess stack level. From this, it can be concluded that the allowed stack level has huge impacts on the coal gangue recycling quantity.

Table 12. Coal output, gangue transportation quantity and total gangue stack quantity from each colliery when the CGPF is located at Site 6 (10^6 tonnes).

φ	Description	β = 0.7	β = 0.8	β = 0.9
40%	Total coal production quantity	37.5707	37.8699	37.2739
	Total gangue transportation quantity	0.3440	0.3956	0.2915
	Total gangue stack quantity	6.1966	6.1895	6.1905
30%	Total coal production quantity	36.4436	36.7338	36.1557
	Total gangue transportation quantity	0.6928	0.6857	0.6432
	Total gangue stack quantity	5.5769	5.5769	5.6893
20%	Total coal production quantity	34.9859	35.2645	34.7095
	Total gangue transportation quantity	1.0616	0.8043	1.0141
	Total gangue stack quantity	4.969	4.969	5.0692
10%	Total coal production quantity	32.1870	32.4453	31.9327
	Total gangue transportation quantity	1.0884	0.9631	0.8812
	Total gangue stack quantity	4.4274	4.338	4.4964
0%	Total coal production quantity	28.9683	29.1990	28.7394
	Total gangue transportation quantity	1.1674	1.1341	1.2131
	Total gangue stack quantity	4.0156	3.9513	4.0512

Proposition 3. *The relaxed coal gangue excess stack level blocks the environment improvement.*

Table 12 shows the total coal output and the total gangue transportation quantity in Yanzhou coal field under different situations. When the allowed excess stack level φ is 10% (take the basic satisfaction degree β = 0.8 as the example), the total coal output is 32.4453×10^6 tonnes, which is a 11.12% growth compared to the situation when $\varphi = 0\%$; the total gangue transportation quantity is 0.9631×10^6 tonnes, a decline of 15.08%. The increase in the total coal production quantity (11.12%) is lower than the decrease in the total gangue transportation quantity (15.08%), and the gap is 0.0396. When φ is changed to 20%, the increase in the total coal production quantity and the decrease in the total gangue transportation quantity is 8.69% and 16.48%, respectively, and the gap is 0.0779. Therefore, the gap between them rises from 0.0396–0.0779. If the government set $\varphi = 30\%$, this occurs again, and the increase in the total coal output is 4.17% and the decrease in total gangue transportation 14.75%; the gap between them grows to 0.1058. A similar result can also be found when $\varphi = 40\%$. Figure 10 shows the changing trend between the increase in coal output and the decrease in gangue transportation quantity under different φ, compared to the allowed excess stack level at 0%. Therefore, it indicates that when the government sets a relaxed excess stack level, the decrease in coal gangue transportation quantity is higher than the increase in coal production quantity, and the gap between them widens when the allowed excess stack level grows. The reasons for this can be found by analyzing Equations (10) and (13). In this situation, when the government sets a very strict environment protection policy, each colliery has to decrease the coal output and make full use of coal gangue transportation capacity to ensure the basic demand. However, when the allowed excess stack level is relaxed, each colliery will increase coal output and decrease coal gangue transportation quantity, especially when the allowed excess stack level is 40% (see in Equation (13)). Based on the above analysis, it can be found that the relaxed excess stack level not only leads to the coal output increase, but also decreases coal gangue transportation quantity. Therefore, it causes a great increase in the coal gangue stack. Obviously, the relaxed excess stack level blocks the environment improvement.

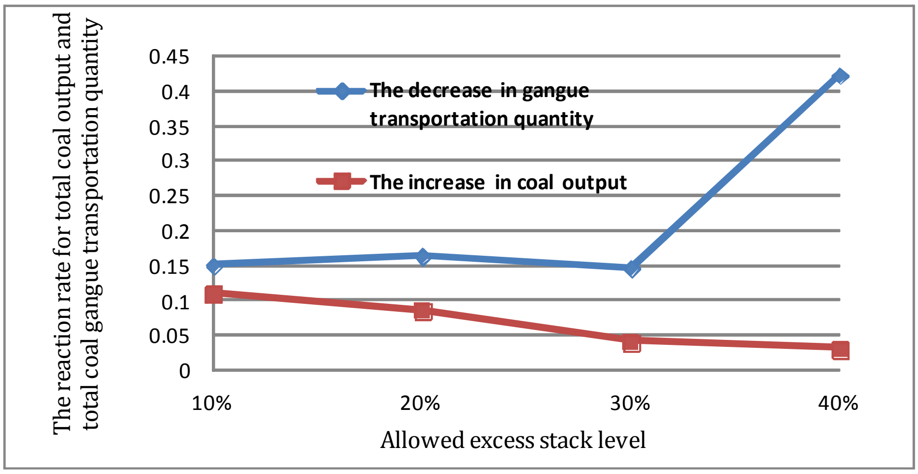

Figure 10. The reaction rate for total coal production quantity and total coal gangue transportation quantity compared to $\varphi = 0\%$ with different allowed excess stack levels.

Proposition 4. *The basic satisfaction degree does not significantly influence the total coal gangue stack in coal fields.*

To ensure site selection equity in the presented facility recycling mechanism, the government is responsible for allocating a relatively satisfactory transportation capacity to each colliery (i.e., Equation (5)). Therefore, to guarantee a basic satisfaction degree for each colliery, the local authority sets a subjective parameter β in Equation (5). Table 6 shows the sensitivity analysis of parameter β when the allowed excess stack level φ is 40%, and Tables 7–9 show the sensitivity analysis of parameter φ under the changing basic satisfaction degree β. Taking $\varphi = 40\%$ as an example, according to the calculation results in Table 12, it can be found that when the government sets the basic satisfaction degree at $\beta = 0.7$ with $\varphi = 40\%$; the coal gangue stack quantity is 6.1966×10^6 tonnes; when the local authority sets $\beta = 0.8$, the coal gangue stack quantity is 6.1895×10^6 tonnes, and it changes only 0.11%. When the local authority sets $\beta = 0.9$, the total stack quantity is 6.1905×10^6 tonnes, which changes only 0.016%. When the allowed excess stack level φ changes to 30%, 20%, 10% and 0%, the results are show in Figure 11, and the same conclusion can be obtained. The above results demonstrates that if the allowed excess stack level φ is fixed, changing basic satisfaction degree β does not significantly influence the total coal gangue stack quantity in coal fields. The reason can be explained by Equation (2), and the total stack quantity is mainly determined by the coal output and coal gangue transportation plan. Nevertheless, when the local authority sets a different satisfaction degree β with a fixed allowed excess stack level, the transportation capacity and the coal production in each colliery change rarely. Compared to huge stack costs, it is more efficient to take advantage of the transportation capacity. Under the circumstances, the changing excess stack level φ, which has huge impacts on coal output, is the main factor influencing the total coal gangue stack quantity.

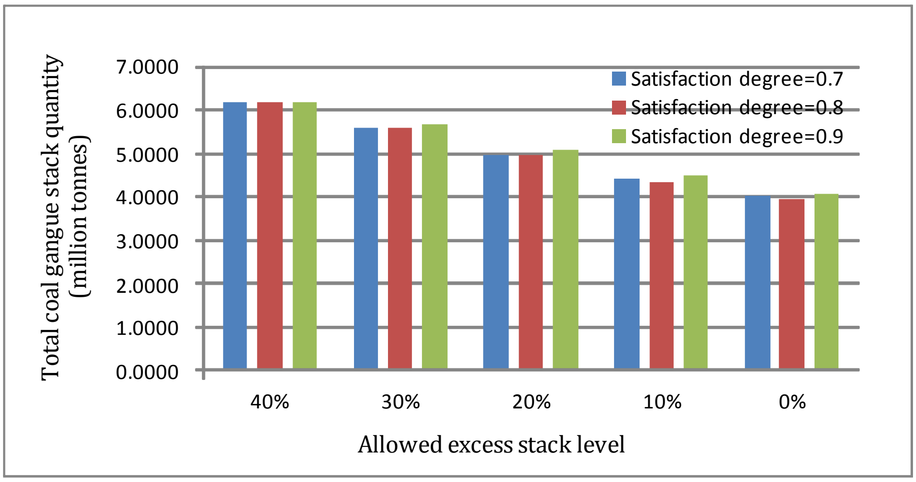

Figure 11. The total coal gangue stack quantity with changing parameters β and φ.

Proposition 5. *Collieries with smaller unit mining gangue coefficients have priority in the gangue facility recycling mechanism.*

When the government changes the environment protection constraint φ, as shown in Tables 6–9 and Figures 6–8, the reaction of each colliery is very different. Taking the situation $\beta = 0.7$ as an example, Figure 8 indicates that when the allowed excess stack level changes from 40% to 30%, the XLZ and DT collieries can adjust the coal gangue transportation plan to guarantee the coal output. However, ST and JN2 collieries have to decrease more coal output to realize the 10% stack reduction target. When the allowed stack level changes from 20% to 10%, the ST and JN2 colliery also have to decrease more coal output to realize the 10% stack reduction target. However, in this situation, the coal output of the two colliery can just meet the basic demand. Under a lower allowed excess stack level, the change margin in coal output and coal gangue transportation quantity of XLZ and DT collieries is relatively small, compared with ST and JN2 collieries. Under the circumstances, the XLZ and DT collieries with smaller mining gangue coefficients can obtain larger transportation capacity in the coal gangue facility recycling mechanism and produce more coal to maximize profits. Based on the above analysis, it can be summarized that collieries with smaller unit mining gangue coefficients have priority in the gangue facility recycling mechanism.

5.2. Management Recommendations

Based on the above application results and discussions, some management recommendations are proposed.

The application results indicate that the CGF construction not only relieves the adverse effects caused by the coal gangue, but also increases the government financial revenue. Furthermore, the GIS technique and the bi-level model used to screen for the optimal CGF site are proven to be an efficient method for the achievement of environmental-economic development goals. The results also indicate that appropriate CGF site selection can reduce coal gangue stack quantities and also assist in ensuring there is no coal shortage in the local region. Developed initially to address the serious environmental pollution problems caused by coal gangue stacks, optimal site selection for a coal gangue facility can also be an efficient revenue making resource for the government.

Further, because of the conflicts between the local authority and the colliery owners, it is of great importance for the government to formulate the appropriate coal gangue excess stack level and the basic satisfaction degree for each colliery. If there are no excess stack level limits or the allowed excess stack limits are too high, collieries will seek to maximize coal output without taking the coal gangue stack level into account, as the larger output will bring in greater profits within the colliery's capacity. However, if the allowed excess stack level is too low, the increased coal gangue stack costs and transportation costs result in coal shortages because the more the quantity of coal produced, the more the amount of coal gangue piled and the more the transportation costs. Hence, to reduce costs, collieries will produce less coal, which may not be enough to meet local coal demand. Using the GIS technique-based bi-level model, the government can combine the actual situation to set up a suitable allowed excess stack level φ and satisfaction degree β. Nevertheless, it is not always a good strategy for the authority to set lower excess stack levels with higher satisfaction degrees. When the allowed excess stack level φ is strict, set a lower value for β to ensure the colliery transportation capacity, which has a big gangue stack quantity in the previous year. In turn, when the allowed excess stack level φ is relaxed, set a higher value for β to ensure the colliery transportation capacity, which has a smaller mining gangue coefficient. Under the above circumstances, even though the allowed stack level is very low, the colliery with big historical stack quantities will make full use of the transportation capacity, and the government's financial revenue will not significantly decline. Meanwhile, when the allowed stack level is very high, the colliery with smaller mining gangue coefficients can increase the coal output, which also increases the government's tax revenue. An appropriate excess stack level ($\varphi = 20\%$) and satisfaction degree ($\beta = 0.8$) can control the amount of stack coal gangue effectively and maximize the local authority's revenue.

6. Conclusions

In this paper, a GIS technique and bi-level programming model are integrated based on the equilibrium strategy with fuzzy variables to deal with a coal gangue facility site identification and selection problem. It fully considers the important influence of the geographic data and the inevitable conflicts between the government and the collieries, while also seeking a trade-off between environmental protection and economic development by limiting coal gangue excess stack levels. To solve the complex bi-level multi-objective programming model, the fuzzy theory and KKT conditions are combined as a solution approach.

The proposed method is applied to a case study in YanZhou coal field, which has six major collieries. After inputting the detailed data into the model and using the generated solution approach, the applicability and effectiveness of the proposed method is demonstrated. The results indicate that a coal gangue facility based on stack reduction contributes to resource recycling and environmental improvement. With the limited stack level, each colliery determines an environmentally-friendly strategy to achieve as large a transportation capacity as possible, which indicates that the proposed model can successfully mitigate the coal-gangue conflicts. From the analysis of different scenarios, a variable excess stack level strategy is developed to ensure a trade-off between environmental protection and economic development. This approach can also be used in other coal fields as a reference for management recommendations to mitigate coal gangue contamination, thereby promoting environmental improvement.

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Abbreviations

The following abbreviations are used in this manuscript:

CGF	coal gangue facility
GIS	geographical information system
KKT	Karush–Kuhn–Tucker
BLMOP	bi-level multi-objective programming
CGF-SS	coal gangue facility-site selection
CGPF	coal gangue power facility
ST	South Tuen
XLZ	Xing longzhuang
BD	Baodian
DT	Dongtan
JN2	Jining No. 2
JN3	Jining No. 3

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