

## Research Article

# Decision-Making on Reuse Modes of Abandoned Coal Mine Industrial Sites in Beijing Based on Environment-Economy-Society Matter-Element Models

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Redevelopment of abandoned coal mine industrial sites (ACMISs) has been one of the critical research topics in recent years. The ecological system of ACMISs, which involves environmental, economic, and social characteristics, is an environment-economy-society (EES) composite system. Many factors with conflicting effects are involved in the sustainable development of this system. The matter-element analysis method presented in this paper can transform counteracting problems among influencing factors into compatible problems. This analytical approach leads to a reduction of the uncertainty of these influencing factors and provides a suitable research method to solve the complexity when selecting the most suitable reuse mode of the ACMIS. In this study, eight state-owned ACMISs in the suburbs of Beijing were investigated, and a suitability evaluation index system based on the EES conceptual framework was built. Targeting four reuse modes, including the residential area, the park, the scientific research and office campus, and the business district, we established a matter-element decision-making model to evaluate the priority of reuse mode selections scientifically. The results of our calculations show that the optimal reuse mode for the Qianjuntai, Muchengjian, and Huapogen ACMISs is the park; for the Da'an Shan and Changgouyu ACMISs is the business district; for the Datai ACMIS is the scientific research and office campus; and for the Wangping ACMIS is the residential area. Since the suitability level of reusing the Anjiatan ACMIS in any of the four reuse modes is relatively low, it is recommended to reserve it for governmental strategically reserved open space. These real cases demonstrate that the research method is feasible and can be applied to reuse mode decisions for similar abandoned coal mines.

## 1. Introduction

China is one of the countries with the longest history of exploiting coal resources in the world. As the “food” and “blood” of the industry, coal mines have made historical contributions to establishing China’s independent and complete industrial system. With the depletion of resources and the cessation of coal mining activities, many abandoned coal mine industrial sites (ACMISs) have been left idle inside the city, inevitably endangering the city’s social, economic, and ecological security. ACMISs have distinct landscape and spatial characteristics and are important carriers of coal mines’ social, economic, cultural, technological, and scientific values. Through reasonable governance and restoration, supplemented by effective planning and configuration,

ACMISs utilization can be regained, freeing up new space for city development and providing an opportunity for the transformation and upgrading of mining areas.

The related research of coal mine wasteland has been one of the hot issues in the international academic field. They have caused huge environmental damage to the area, such as air pollution, land collapse, soil pollution, and so on. Therefore, the reuse of abandoned coal mines has been the research focus of many experts and scholars, especially the decision-making of the reuse of abandoned industrial sites.

At present, the research on coal mine wasteland mainly involves environmental pollution [1, 2], reuse potential [3], reuse decision-making [4–6], and reuse benefit evaluation [7]. Related studies reflect the site conditions of coal mine wasteland from multiple perspectives and evaluate the

benefits of coal mine wasteland reuse. From the perspective of evaluation objectives and selected indicators, the current evaluation of the decision-making of coal mine wasteland reuse mainly includes five aspects: reuse policy, views of stakeholders, influencing factors of reuse, reuse potential, and reuse mode. Ahmad et al. [8] took Pakistan as an example and constructed a reuse evaluation index system for abandoned land in developing countries based on three reuse modes (residential areas, ecoindustrial campuses, and commercial markets) [9]. Josef et al. [10] and Stanislav et al. [11] studied the preference of urban residents for the reuse of local abandoned land. Josef et al. [12] and Stanislav et al. [13] conducted questionnaire surveys to study the public's views on the industrial heritage tourism destinations developed from abandoned land. Mateus et al. [14] studied the sustainable application of crucial stakeholders in the development of abandoned mining areas in Portugal by means of several decision-supporting tools (M-MACBETH, MACBETH Voting, and Web-MACBETH). Marija et al. [15] formulated important standards for different plans of reusing abandoned land in Vilnius of Lithuania based on a geographic information system (GIS) analysis platform combined with expert evaluation and the Delphi method. Wang [16] and Dou et al. [17] have constructed suitability evaluation systems for the reclamation of ACMISs into land for agriculture, forestry, and fishery. Hou et al. [18] adopted factor analysis and structural equation modeling (SEM) to explore the driving force for a sustainable renewal of ACMISs. Liu et al. [19] used the land competition model to evaluate the land competitiveness of ACMISs. In addition, in terms of the sustainable development of ACMISs in Beijing, the current academic results are mainly concentrated on ecosystem service [20], ecotourism [21], and ecological restoration [22]. In any case, most studies have only established an evaluation index system for single or multiple reuse modes. Such evaluation results are not scientific and accurate enough.

The ecological system of the ACMIS, which involves environmental, economic, and social characteristics, is an EES composite system. The decision-making of reuse modes involves the suitability of a single system and puts more emphasis on the overall suitability of the EES composite system. Many variables affect the sustainable development of this composite system, and conflicts are likely to occur. The most frequently used methods are the extreme condition method [23], principal component analysis (PCA) [24], and artificial neural networks (ANNs) [25]. The traditional fuzzy evaluation method, grey relational analysis method, and neural network method have certain subjectivity in determining the weight and membership degree, which cannot guarantee the objectivity and credibility of the evaluation results. Analytic hierarchy process (AHP) and fault tree analysis (FTA) have poor processing ability for non-linear structures, and the calculation process is complex when there are many samples. The probability evaluation method is required to describe the uncertainty in the system accurately, and its evaluation results are not accurate and practical, so it needs to be improved. The matter-element model employed in this study is a decision-making method

developed based on extension theory [26]. It does not simply consider the optimization of quantitative relations but uses the matter-element transformation to reduce contradictions among factors. It transforms a contradictory problem into a compatible problem and abstracts a complex problem into a formal model, making the decision more objective and detailed. Therefore, the matter-element model can solve to a certain extent the problems of the excessive influence of subjective indices and strong uncertainty of index weights [27]. In the field of urban planning, the matter-element model has been widely used in land ecological security [27, 28], urban land intensive use [29], and ecological benefits [30]. Therefore, it can provide a suitable research method for solving the complexity of reuse mode decisions for ACMISs.

To sum up, exploring the diversity of reuse patterns and scientific calculation methods has always been the core issue of reuse decision-making. Firstly, in the selection of indicators, indicators with different tendencies are selected in the evaluation system for different reuse modes. Secondly, in terms of the calculation method, the matter-element model that can make the index data more compatible is selected. Finally, eight abandoned industrial sites in the Jingxi Coal Mine, which are located in the metropolis of Beijing where the contradiction between humans and land is very prominent, are selected as the research objects. The purpose is to analyze quantitatively the decision-making of the reuse of ACMISs affected by the complex environment of environment, economy, and society and provide a scientific basis for adjusting the land use structure of mining wasteland.

## 2. Overview of the Districts Studied and Sources of Data

*2.1. Overview of the Districts Studied.* The Jingxi Coal Mine, located in the Mentougou and Fangshan Districts in Beijing's suburbs, was once an important energy base in the capital city. During the time frame of 2016 to 2020, the Beijing Jingmei Group has successively shut down the coal mines of Changgouyu, Wangpingcun, Muchengjian, Qianjuntai, Da'anshan, and Datai, in response to the government's policy requirements for resolving "non-capital functions". Prior to this date, production in the Anjatan and Huapogen coal mines had ceased for many years. As an example, the ground and underground structures and ancillary facilities of the Jingxi Coal Mine industrial sites are worth more than a billion RMB [31]; the losses will be tremendous if these mines are completely abandoned. Therefore, the realization of efficient reuse of these resources with the goal to enable "successful cross-border transformation" of the Jingxi Coal Mine is one of the critical topics of sustainable urban planning in Beijing.

The Jingxi Coal Mine is located mainly in the Mentougou and Fangshan Districts of Beijing. The coal mine with a length of 45 km from east to west and a width of 35 km from north to south covers 1,019 km<sup>2</sup>. Its subordinate coal mines mainly include Qianjuntai, Muchengjian, Wangping, Da'anshan, Changgouyu, Huapogen, Anjatan, and Datai (Figure 1).

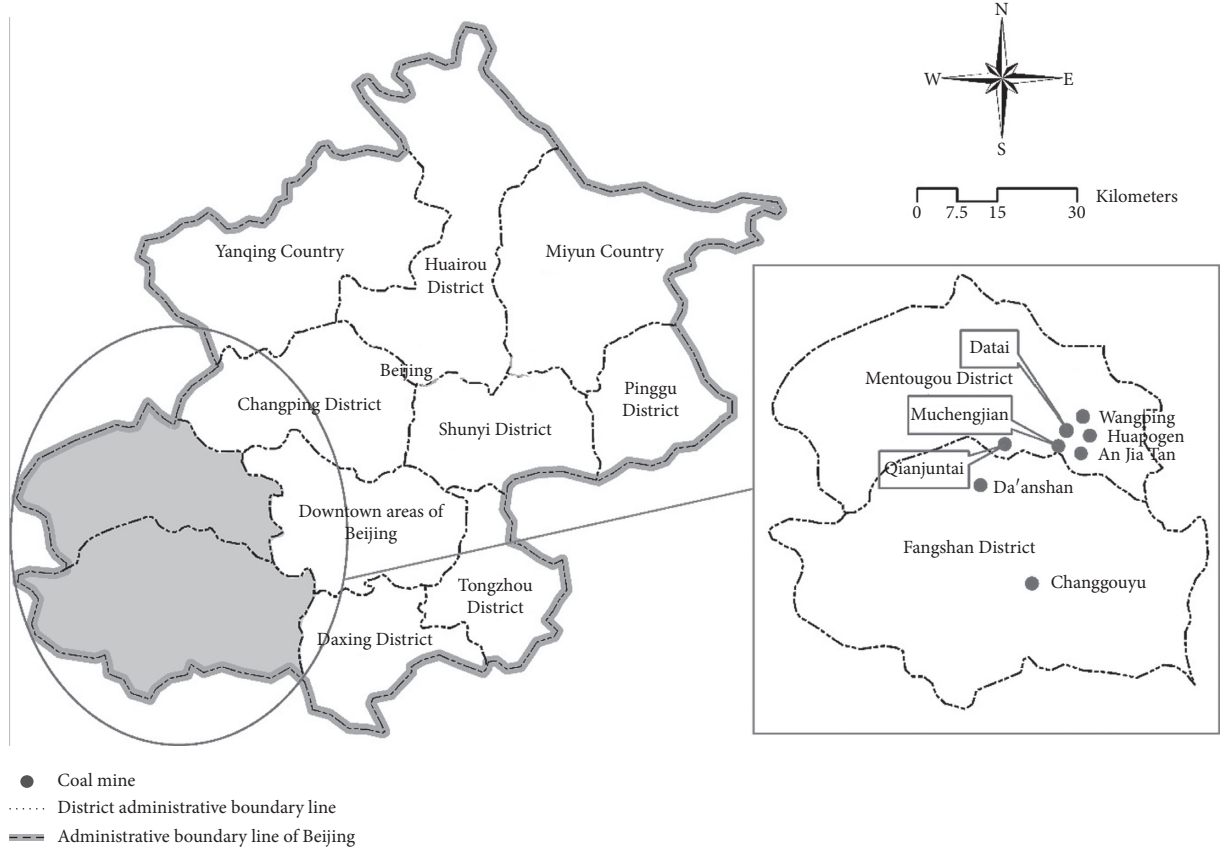


FIGURE 1: Spatial distribution of ACMISs of the Jingxi Coal Mine [2].

**2.2. Data Sources.** The primary data sources are described as follows. (1) Google Earth high-precision images of the Fangshan and Mentougou Districts were used to create a distribution map of research objects and determine their location conditions. (2) Reports on ACMISs from the Jingmei Group were used to confirm the status of each ACMIS. (3) Municipal (the years 2016–2030), district (the years 2006–2020), and township planning documents were used to understand government investment tendencies. (4) Blueprints of the ACMISs were used to confirm their hydrological and topographical conditions. (5) Additional data were obtained from field surveys and interviews to revise and improve the already collected data and determine the demands of all stakeholders.

### 3. Methods (Matter-Element Model)

Matter-element extension analysis is a mathematical analysis method proposed by Cai Wen, a Chinese scholar, to solve the problem of uncertainty. The concept of distance in real variable function is extended to the distance from point to interval on the real axis, and the value range of the correlation function is expanded. It transforms the determined value of each evaluation index into an interval value, which improves the degree of the evaluation object that belongs to the set. The calculation process includes five steps: building the object model, determining the classical domain and node domain, determining the correlation degree, determining the index weight, and determining the suitability level.

**3.1. Construction of the Matter-Element Model for Evaluation Objects.** According to the matter-element extension method, the name of the object to be evaluated is set as  $P$ , its characteristic vector as  $c$  (evaluation index), and its characteristic value  $v$ , which, when combined, constitute a matter element  $R = (P, c, v)$  [32] for suitable reuse of the ACMIS.

If  $R_o$  is the basic data information of the ACMIS obtained after collection, calculation, and analysis,  $y_i$  represents the specific value of the data information of  $P_o$  on the  $i$ -th ( $i = 1, 2, \dots, n$ ) evaluation index  $c_i$ , and  $P_o$  is the object to be evaluated, then

$$R_o = (P_o, c_n, y_i) = \begin{bmatrix} P_o, & c_1, & y_1 \\ & c_2, & y_2 \\ & \vdots & \vdots \\ & c_n, & y_n \end{bmatrix}. \quad (1)$$

**3.2. Determination of Classical Domain and Node Domain.** The object  $P$  to be evaluated is supposed to have  $m$  levels ( $m = 1, 2, 3, 4$ ), where  $v_{mi} = [\alpha_{im}(x), \beta_{im}(x)]$  represents the evaluation standard of the  $m$ -th level reuse mode ( $P_{om}$ ) with respect to the  $i$ -th evaluation index  $c_i$  ( $i = 1, 2, \dots, n$ ). The matter-element matrix composed of  $v$  is called the classical domain of object  $P$ , which can be expressed as follows:

$$R_{om} = (P, c, v) = \begin{bmatrix} P_{om} & c_1 & v_{m1} \\ & c_2 & v_{m2} \\ & \vdots & \vdots \\ & c_n & v_{mn} \end{bmatrix} = \begin{bmatrix} P & c_1 & [\alpha_{m1}(x), \beta_{m1}(x)] \\ & c_2 & [\alpha_{m2}(x), \beta_{m2}(x)] \\ & \vdots & \vdots \\ & c_n & [\alpha_{mn}(x), \beta_{mn}(x)] \end{bmatrix}, \quad (2)$$

where  $c_i$  ( $i = 1, 2, 3, \dots, n$ ) is set as the  $i$ -th evaluation index for reusing the ACMIS in four reuse modes, the value range of which is shown in Tables 1–4.  $v_i = [\alpha_i(x), \beta_i(x)]$  represents the value range of the evaluation index  $c_i$ , which is the node domain of the object  $P$ . Then, the node domain of the reuse mode evaluation of the AMCIS can be expressed as follows:

$$R_p = \begin{bmatrix} P & c_1 & v_{p1} \\ & c_2 & v_{p2} \\ & \vdots & \vdots \\ & c_n & v_{pn} \end{bmatrix} = \begin{bmatrix} P & c_1 & [\alpha_{p1}(x), \beta_{p1}(x)] \\ & c_2 & [\alpha_{p2}(x), \beta_{p2}(x)] \\ & \vdots & \vdots \\ & c_n & [\alpha_{pn}(x), \beta_{pn}(x)] \end{bmatrix}, \quad i = 1, 2, \dots, n. \quad (3)$$

According to equations (2) and (3), the value range of the characteristic values of the suitability evaluation levels of reuse modes for all AMCISs constitutes the node domain. In contrast, the value range of the characteristic values of the suitability evaluation levels of the reuse mode for an individual AMCIS constitutes the classical domain, and  $Rom^{RP_o}$ .

The node domain data need to be nondimensional since the units of the different evaluation indices are not unified and cannot be directly compared. We used the min-max normalization method to standardize the indices in the node domain, and the equations are as follows:

$$\text{positive indices: } Y_{mi} = \frac{X_{mi} - \min X_{mi}}{\max X_{mi} - \min X_{mi}}, \quad (4)$$

$$\text{negative indices: } Y_{mi} = \frac{\max X_{mi} - X_{mi}}{\max X_{mi} - \min X_{mi}}, \quad (5)$$

where  $Y_{mi}$  is the standardized value of the  $i$ -th index,  $X_{mi}$  is the original value of the  $i$ -th index, and  $\max X_{mi}$  and

$\min X_{mi}$  are the maximum and minimum of the  $i$ -th index, respectively.

**3.3. Determination of the Correlation Degree.** The elementary correlation function  $K(x)$  can be used to describe the correlation degree of the object  $P_o$  to a certain interval, as shown in the following equation:

$$k_m(v_i) = k_m(v_{pi}) \begin{cases} \frac{-\rho(v_i, V_{mi})}{|V_{mi}|}, & v_i \in V_{mi}, \\ \frac{\rho(v_i, V_{mi})}{\rho(v_i, V_{pi}) - \rho(v_i, V_{mi})}, & v_i \notin V_{mi}, \end{cases} \quad (6)$$

and from the following equation:

$$\begin{aligned} \rho(v_i - V_{mi}) &= \left| v_i - \frac{1}{2}(a_{mi} + b_{mi}) \right| - \frac{1}{2}(b_{mi} - a_{mi}), \quad (i = 1, 2, 3, \dots, n; m = 1, 2, 3, 4), \\ \rho(v_i, V_{pi}) &= \left| v_i - \frac{1}{2}(a_{pi} + b_{pi}) \right| - \frac{1}{2}(b_{pi} - a_{pi}), \quad (i = 1, 2, 3, \dots, n), \\ |V_{mi}| &= |b_{mi} - a_{mi}|, \end{aligned} \quad (7)$$

where  $k_{mv_i}$  is the conformity degree between the matter-element level and the evaluation level. Its value range covers the entire real number axis, representing the affiliation degree of each index of the object to be evaluated with respect to each evaluation level [45].

**3.4. Determination of the Index Weight.** According to the evaluation system's characteristics and evaluation indices, an improved analytical hierarchy process (IAHP) was used to calculate the index weight. Since the sorting problem under

multicriteria requires higher calculation accuracy, we chose the  $e0/5 \sim e8/5$  exponential scaling method. This approach has a smaller calculation error and a better fit to the scaling weight when constructing the judgment matrix,  $A$  [43, 46]. The weight of each index was obtained, and a consistency test was conducted.

Compared with the classical analytic hierarchy process, IAHP can construct the judgment matrix more accurately and make the judgment result more reasonable. Its specific steps are as follows: establishing comparison matrix  $A_{ij} \rightarrow$  importance ranking index  $\gamma_{\max} \rightarrow$  constructing

TABLE 1: Suitability evaluation system and criteria of reusing an ACMIS to a park.

Layer criterion	Layer index	Quantitative index	Level			
			I	II	III	IV
Environment	Vegetation coverage	Vegetation index (NDVI)	[85, 100]	[65, 85]	[45, 65]	[0, 45]
	Site slope	Slope	[0, 3]	[3, 7]	[7, 15]	[15, 30]
	Geological hazard risk	Distribution map of debris flow hazards in Beijing in 2018	Nonprone area	Low-prone area	Moderate-prone area	High-prone area
	Landscape	$D_i = \sum_{i=1}^n C_{if} (L_n - L_a) (3)$	[4, 8]	[2, 4]	[1, 2]	[0, 1]
Economy	Public transportation coverage	Distance to bus station (km)	[0, 0.5]	[0.5, 1]	[1, 2]	[2, 3]
	Distribution of nearby roads	Distance to main road (km)	[0, 0.5]	[0.5, 1]	[1, 1.5]	[1.5, 2]
	The proportion of tertiary industry	The proportion of tertiary industry in 2018 (%)	[40, 60]	[30, 40]	[20, 30]	[20, 0]
Society	Business service accessibility	As in equation (1)	[3, 4]	[2, 3]	[1, 2]	[0, 1]
	Cultural tourism concentration	As in equation (2)	[85, 100]	[75, 85]	[60, 75]	[0, 60]
	Building adaptability potential	The potential of site constructions and structure reuse as park facilities	High	Moderate	Low	Very low
	Culture value	Cultural heritage value of mine park	High	Moderate	Low	Very low
	Popular science value	Popular science value of mine park	High	Moderate	Low	Very low
	Preserve authenticity and integrity	Preservation level of mine authenticity and integrity	High	Moderate	Low	Very low
	Management status	Performance of the mine management team	High	—	—	Low
	Green area per capita	Green area per capita in 2018 (m <sup>2</sup> )	[40, 60]	[25, 40]	[10, 25]	[0, 25]
	Government or corporate tendency	Propensity for site reuse as a park	High	Moderate	Low	Very low

Note. In equation (3),  $C$  = landscape environment weight;  $L$  = distance from landscape to the site; and  $L_a$  = perception insensitive distance.

TABLE 2: Suitability evaluation system and criteria of reusing an ACMIS as a scientific research and office campus.

Layer criterion	Layer index	Quantitative index	Level			
			I	II	III	IV
Environment	Geological hazard risk	Distribution map of debris flow hazards in Beijing in 2018	Nonprone area	Low-prone area	Moderate-prone area	High-prone area
	Site slop	Slope	[0, 5]	[5, 8]	[8, 15]	[15, 30]
	Geological conditions	Soil texture	Loamy	Sandy loam	Clay soil	Fine-silty
	Heavy metal pollution	Hakanson potential ecological risk index	[0, 150]	[150, 300]	[300, 600]	[600, 1,000]
Economy	Polluted wind	The extent to which the site is affected by polluted wind	Very low	Low	Moderate	High
	Public transportation coverage	Distance to bus station (km)	[0, 0.5]	[0.5, 1]	[1, 2]	[2, 3]
	Distance to main road	Distance to main road (km)	[0, 0.5]	[0.5, 1]	[1, 1.5]	[1.5, 3]
	Enterprise income	Production capacity of each coal mine in 2016	[150, 200]	[100, 150]	[50, 100]	[0, 50]
	Research funding input	2015–2018 average scientific research expenditure (10 thousand RMB/year)	[3,000, 4,000]	[2,000, 3,000]	[1,000, 2,000]	[0, 1,000]
Society	Business service accessibility	As in Equation (1)	[3, 4]	[2, 3]	[1, 2]	[0, 1]
	Population distribution	2018 town population density (residents/km <sup>2</sup> )	[900, 1,200]	[400, 900]	[100, 400]	[0, 100]
	Construction adaptability potential	Potential for reuse as office buildings	High	Moderate	Low	Very low
	Construction engineering stability	Land subsidence and foundation bearing capacity	High	Moderate	Low	Very low
	Educational facility coverage	Distance to research institutions and schools (km)	[0, 0.5]	[0.5, 1]	[1, 1.5]	[1.5, 3]
	Government or corporate tendency	Site reuse potential as a scientific research and office campus	High	Moderate	Low	Very low



TABLE 3: Suitability evaluation system and criteria of reusing an ACMIS as the business district.

Layer criterion	Layer index	Quantitative index	Level			
			I	II	III	IV
Environment	Site slope	Slope	[0, 5]	[5, 15]	[15, 25]	[25, 35]
	Geological hazard risk	Distribution map of debris flow hazards in Beijing in 2018	Nonprone area	Low-prone area	Moderate-prone area	High-prone area
	Geological conditions	Measured soil texture	Loamy	Sandy loam	Clay soil	Fine-silty
	Heavy metal pollution	Hakanson potential ecological risk index	[0, 150]	[150, 300]	[300, 600]	[600, 1,000]
	Polluted wind	The extent to which the site is affected by polluted wind	Very low	Low	Moderate	High
	Water cleanliness	Mine water purification treatment capacity of site	High	Moderate	Low	Very low
Economy	Public transportation coverage	Distance to bus station (km)	[0, 0.5]	[0.5, 1]	[1, 2]	[2, 3]
	Distance from district center	Distance from district center (km)	[0, 40]	[40, 55]	[55, 70]	[70, +∞]
	Disposable income of urban residents	Per capita disposable income of urban residents in 2018 (10 thousand Yuan)	[5, 8]	[4, 5]	[2, 4]	[0, 2]
	Disposable income of residents	Per capita net income of residents in 2018 (10 thousand Yuan)	[3, 5]	[2, 3]	[1, 2]	[0, 1]
	Consumption level of residents	Total retail sales of consumer goods in 2018 (100 million Yuan)	[200, 300]	[100, 200]	[50, 100]	[0, 50]
	Commercial concentration	As in equation (2)	[85, 100]	[75, 85]	[60, 75]	[0, 60]
Society	Public service accessibility	As in equation (1)	[4, 10]	[2, 4]	[1, 2]	[0, 1]
	Distance to scenic spots	Distance to the nearest scenic spot (km)	[2, 3]	[3, 4]	[4, 5]	[5, +∞]
	Population distribution	2018 town population density (residents/km <sup>2</sup> )	[900, 1,200]	[400, 900]	[100, 400]	[0, 00]
	Population	2018 town population (10 thousand RMB)	[2, 4]	[1, 2]	[0.6, 1]	[0, 0.6]
	Building adaptability potential	Reuse potential as a commercial building	High	Moderate	Low	Very low
	Construction engineering stability	Land subsidence and foundation bearing capacity	High	Moderate	Low	Very low
	Government or corporate tendency	Propensity to reuse the site as a commercial service area	High	Moderate	Low	Very low

TABLE 4: Classical and node domains applied to the suitability evaluation of reusing Da'anshan ACMIS as a residential area.

Index	Classical domain				Node domain
	I	II	III	IV	
Site slope	[0.86, 1]	[0.57, 0.86]	[0.29, 0.57]	[0, 0.29]	[0, 1]
Geological hazard risk	[0.98, 1]	[0.97, 0.98]	[0.67, 0.97]	[0, 0.67]	[0, 1]
Heavy metal pollution	[0.85, 1]	[0.75, 0.85]	[0.40, 0.70]	[0, 0.40]	[0, 1]
Ecological sensitivity	[0.63, 1]	[0.50, 0.63]	[0.25, 0.50]	[0, 0.25]	[0, 1]
Polluted wind	[0.75, 1]	[0.5, 0.75]	[0.25, 0.50]	[0, 0.25]	[0, 1]
Water cleanliness	[0.75, 1]	[0.5, 0.75]	[0.25, 0.50]	[0, 0.25]	[0, 1]
Noise level	[0.75, 1]	[0.5, 0.75]	[0.25, 0.50]	[0, 0.25]	[0, 1]
Public transportation coverage	[0.83, 1]	[0.67, 0.83]	[0.33, 0.67]	[0, 0.33]	[0, 1]
Municipal facilities coverage	[0.75, 1]	[0.5, 0.75]	[0.25, 0.50]	[0, 0.25]	[0, 1]
Distance from district center	[0.78, 1]	[0.69, 0.78]	[0.61, 0.69]	[0, 0.61]	[0, 1]
Proportion of tertiary industry	[0.67, 1]	[0.50, 0.67]	[0.33, 0.50]	[0, 0.33]	[0, 1]
Real estate development investment	[0.75, 1]	[0.50, 0.75]	[0.25, 0.50]	[0, 0.25]	[0, 1]
Public service accessibility	[0.40, 1]	[0.20, 0.40]	[0.10, 0.20]	[0, 0.10]	[0, 1]
Population distribution	[0.75, 1]	[0.33, 0.75]	[0.08, 0.33]	[0, 0.08]	[0, 1]
Commercial concentration	[0.85, 1]	[0.75, 0.85]	[0.60, 0.75]	[0, 0.60]	[0, 1]
Construction adaptability potential	[0.75, 1]	[0.5, 0.75]	[0.25, 0.50]	[0, 0.25]	[0, 1]
Construction engineering stability	[0.75, 1]	[0.5, 0.75]	[0.25, 0.50]	[0, 0.25]	[0, 1]
Government or corporate preferences	[0.75, 1]	[0.5, 0.75]	[0.25, 0.50]	[0, 0.25]	[0, 1]

judgment matrix  $b_{ij}$  → finding transfer matrix  $C_{ij}$  of  $b_{ij}$  → finding optimal transfer matrix  $D_{ij}$  of  $C_{ij}$  → finding

quasi optimal consistent matrix  $b'_{ij}$  of  $b_{ij}$  → finding weight vector  $W_i$  of  $b'_{ij}$ .  
Among them

$$\begin{aligned}
 A_{ij} &= \begin{cases} 0, & \text{element } i \text{ is not important in element } j, \\ 1, & \text{element } i \text{ is as important as element } j, \\ 2, & \text{factor } i \text{ is more important than factor } j, \end{cases} \\
 \gamma_{\max} &= \max\{\gamma_i\} = \max\left\{\sum_{i=1}^n A_i\right\}, \\
 c_{ij} &= lgb_{ij}, b_{ij} \text{ Is the judgment matrix } B_{ij} \text{ element,} \\
 b'_{ij} &= 10^{d_{ij}} = 10^{\frac{1}{n} \sum_{k=1}^n (c_{ik} - c_{jk})}, \\
 \overline{W}_l &= \sqrt[n]{\prod_{j=1}^n b'_{ij}}, \\
 W_i &= \frac{\overline{W}_l}{\sum_{i=1}^n \overline{W}_l}.
 \end{aligned} \tag{8}$$

**3.5. Determination of Suitability Levels.** The correlation degree  $K_m(v_i)$  of each object with the  $m$ -th suitability level can be expressed as follows:

$$K_m(R_o) = \sum_{i=1}^n \omega_i K_m(v_i). \tag{9}$$

Finally, the affiliation level of the ACMIS is determined according to the principle of the maximum correlation degree, and a specific value is used to reflect to which degree the ACMIS belongs to this level.  $mo$  represents the affiliation level of the reuse mode for the ACMIS to be evaluated, which can be expressed as follows:

$$K_{mo}(R_o) = \max_{m \in \{1,2,3,4\}} K_m(R_o), \tag{10}$$

where  $w_i$  is the weight of the  $i$ -th index, and  $K_{mo}(R_o)$  is the comprehension correlation degree of the  $mo$ -th level.

## 4. Index System Construction

**4.1. EES Model.** The ACMIS is a composite ecosystem with characteristics involving the environment, economy, and society. The ACMIS reuse mode decision pursues the comprehensive suitability of these three subsystems, rather than that of a single system. The EES conceptual synergy model has excellent applicability for constructing a composite suitability evaluation system of the reuse mode for the ACMIS.

**4.2. Selection and Quantification of Indices.** According to various planning documents, policies, and regulations, and in combination with the development positioning of ACMISs of the Jingmei Group, as well as interviews with

residents, we explored four reuse modes for ACMISs of the Jingxi Coal Mine based on the important functional positioning of the Mentougou and Fangshan Districts as the “ecological conservation area” of Beijing. The four reuse modes are the residential area, the park, the scientific research and office campus, and the business district. Based on the EES model, the suitability evaluation system for each of the four reuse modes was constructed. Finally, the suitability levels of the four reuse modes for each ACMIS from high to low were determined to be I (highly suitable), II (moderately suitable), III (barely suitable), and IV (unsuitable).

Based on previous results [47–50], evaluation indices were selected from three dimensions, including environment, economy, and society, to construct an evaluation index system. Among them, the index selection related to the residential area is mainly based on the “Urban Residential Area Planning and Design Code GB50180-93 (2016 Edition)” and “Residential Building Code GB50368-2005”. The selection of indices related to the park mainly refers to the “Mining Geological Environment Protection Regulations” (Ministry of Land and Resources Order (2003) No. 44), “Notice on Declaring National Mine Parks” (Ministry of Land and Resources Order (2004) No. 256), and “Park Design Specification GB51192-2016” from the Ministry of Land and Resources. The selection of suitability indices related to the scientific research and office campus and business district is mainly based on the “General Principles of Civil Architecture Design GB50352-2005”. In addition, the local characteristics of the site and its surrounding areas and consultant of relevant experts were also considered to determine the reuse mode evaluation indices finally.

In the process of quantitative calculation, the qualitative indices that are difficult to quantify were assigned values from low to high: 0–2, 2–4, 4–6, and 6–8. Among the

quantitative indices, the shortest distance was obtained for distance-related indices using the buffer analysis function of ArcGIS 10.2.

**4.2.1. Environmental Indices.** Environmental indices may reflect the topographical conditions, pollution status, and geological hazard risks of the ACMIS. These indices are mainly assigned based on documents, that is, mine closure reports, land reclamation plans, social responsibility reports, and field surveys. Since debris flow is the main geological disaster in Beijing's western mountainous area, the geological disaster risk of the ACMIS was determined based on the distribution of debris flow disaster sensitivity in Beijing in 2018 [51]. The Hakanson potential pollution risk index [52] was applied to assess the pollution degree by heavy metals, graded according to the environmental risk grade for heavy metals in soils of Beijing. The ecological sensitivity was determined by using the shortest distance between the ACMIS and ecologically sensitive areas, that is, rivers and mountains; the closer the distance, the higher the ecological sensitivity and the lower the suitability level. The cleanliness of water resources was determined according to the water purification processing capacity of each coal mine described in the "2016 Social Responsibility Report of Beijing Haohua Energy Co., Ltd." The noise degree was estimated by the distance between the ACMIS and the railway or main road; the higher the noise degree, the lower the suitability level.

The Mentougou and Fangshan Districts are "ecological conservation areas" in Beijing; the weights of environmental indices are slightly higher than those of economic and social indices. Among the environmental indices, the security of residential areas, parks, and business districts is the primary consideration; therefore, the risk of geological disasters has the highest weight. The geological condition of the ACMIS is slightly more important for the scientific research and office campus in terms of constructing the integrated mining area as an ecological restoration laboratory, geology research institute, and so on than the risk of geological disasters.

**4.2.2. Economic Indices.** Economic indices primarily include distance-related factors such as public transportation coverage and the distance from the district center. The proportion of tertiary industry and residents' income was obtained from the Mentougou and Fangshan Districts' statistical yearbooks.

Among these indices, the real estate investment level has the most significant impact on the construction trends of the residential area. The nearby public transportation covering certain areas determines the vitality of this area after being transformed into a park to a certain extent. The income of the enterprise and the local scientific research funding have significant influences on the construction of the scientific

research and office campus. The consumption level of nearby residents significantly affects the site's commercial value and is, therefore, the primary consideration of the business district.

**4.2.3. Social Indices.** Social indices mainly include the accessibility of public services, the concentration of cultural tourism, adaptability and transformation potential of constructions, mine park value, and government or corporate preferences. The accessibility of public services and commercial services was calculated based on the "Beijing Residential Public Service Facilities Allocation Index" (Jingzhengfa (2015) No. 7) and the perspective of the so-called "living circle". The minimum distance model for accessibility evaluation and weighted travel time was used as the accessibility evaluation standard. Indices related to government or corporate preferences reflect the probability of the government or a corporate enterprise to reuse the ACMIS.

Among these indices, the population density around the ACMIS determines the local demand for residential areas to a certain extent. The cultural tourism concentration affects tourist attraction to the park. The distribution of educational facilities affects scientific research and office campus activities. The commercial service concentration reflects the business vitality around the ACMIS, which is the most critical index for the business district development.

The suitability evaluation system and criteria of the four reuse modes for ACMISs based on the EES model are summarized in Tables 1–3 and 5.

## 5. Empirical Analysis and Results

**5.1. Decision-Making Process Analysis.** In this study, a total of 32 decision-making processes were involved in the analysis of four different reuse modes of eight ACMISs of the Jingxi Coal Mine. The suitability evaluation of reusing the Da'an Shan ACMIS as a residential area was taken as an example to describe the calculation process in detail. Results of the decision-making processes of other reuse modes can be obtained in a similar way.

**5.1.1. Construction of Matter-Element of Classical and Node Domains.** The classical and node domains of the indices were obtained after standardization and non-dimensionalization of the indices (Table 4).

**5.1.2. Construction of Matter-Element Model.** Various indices of the Da'an Shan ACMIS were first standardized, and according to equation (4), the matter-element model for reusing Da'an Shan ACMIS as a residential area was constructed as follows:



TABLE 5: Suitability evaluation system and criteria for reusing an ACMIS as a residential area.

Layer criterion	Layer index	Quantitative index	Level			
			I	II	III	IV
Environment	Site slope	Slope calculated by ArcGIS	[0, 5]	[5, 15]	[15, 25]	[25, 30]
	Geological hazard risk	Distribution map of debris flow hazards in Beijing in 2018	Nonprone area	Low-prone area	Moderate-prone area	High-prone area
	Heavy metal pollution	Hakanson potential pollution risk index	[0, 150]	[150, 300]	[300, 600]	[600, 1,000]
	Ecological sensitivity	The distance between the site and the ecologically sensitive area (km)	[2.5, +∞]	[2, 2.5]	[1, 2]	[0, 1]
	Effect of polluted wind	The extent to which the site is affected by polluted wind	Very low	Low	Moderate	High
	Water cleanliness	Mine water purification treatment capacity at the site	High	Moderate	Low	Very low
	Noise degree	Roads or railways passing through the site	None	Only common roads	Only railway	Both
Economy	Public transportation coverage	Distance to bus station (km)	[0, 0.5]	[0.5, 1]	[1, 2]	[2, 3]
	Municipal facility coverage	Completion status of the municipal infrastructure of the site	Yes	—	—	No
	Distance from district center	Distance from district center (km)	[0, 30]	[30, 40]	[40, 50]	[50, 100]
	The proportion of tertiary industry	The proportion of tertiary industry in 2018 (%)	[40, 60]	[30, 40]	[20, 30]	[20, 0]
	Real estate development investment	2015–2018 district real estate development investment average (100 million/year)	[300, 400]	[200, 300]	[100, 200]	[0, 100]
Society	Accessibility of public services	$A_i = \sum_{j=1}^n a_n \times d/L_n$ (1)	[4, 10]	[2, 4]	[1, 2]	[0, 1]
	Population distribution	Population density in 2018 (person/km <sup>2</sup> )	[250, 350]	[150, 250]	[100, 150]	[0, 100]
	Commercial concentration	$S_i = \begin{cases} 100, & D_i \leq 2.8 \\ 100(D_{\max} - D_i)/D_{\max} - 2.8, & D_i > 2.8 \end{cases}$ (2)	[85, 100]	[75, 85]	[60, 75]	[0, 60]
	Construction adaptability potential	Potential for reuse as residential ancillary facilities	High	Moderate	Low	Very low
	Construction engineering stability	Land subsidence and foundation bearing capacity	High	Moderate	Low	Very low
	Government or corporate tendency	Propensity to reuse the site as a residential area	High	Moderate	Low	Very low

Note. In equation (1),  $a$  = weight of facility;  $L$  = distance from facility to site; and  $d$  = service radius of the facility. In equation (2),  $D_{\max}$  = maximum distance between commercial facility and site; and  $D_i$  = distance between commercial facility and site. Construction adaptability potential and engineering stability refer to the incorporation of existing constructions (structures) into the residential area, park, scientific research and office campus, and business district constructions in terms of structure, space, physical life, and foundation stability. Several experts and scholars have comprehensively evaluated the adaptability and transformation potential of existing constructions (structures) for residential, park, office, commercial, and other purposes.

$$R_0 = (p_0, c_n, \gamma_n) = \begin{bmatrix} p_0 & \text{site slope} & 9.1 \\ & \text{geological hazard risk} & 0.04 \\ & \vdots & \vdots \\ & \text{construction engineering stability} & 5 \\ & \text{government or corporate tendency} & 1 \end{bmatrix}. \quad (11)$$

**5.1.3. Determination of Correlation Degree and Index Weights.** According to equation (7), the indices' correlation degrees of reusing Da'anshan ACMIS as a residential area were calculated and sorted. The correlation degree corresponding to the maximum correlation coefficient of each index is the judgment level. The correlation degree matrix was constructed by the IAHP method, and each index weight was determined. As shown in Table 6, there are six evaluation indexes that are determined as grade I, which are conducive to the reuse of Da'anshan ACMIS as a residential area. There are four evaluation indexes that are determined as glass IV, which greatly hinder Da'anshan ACMIS' reuse into a residential area.

**5.1.4. Determination of Suitability Levels.** The results show that the suitability grade of Da'anshan ACMIS for housing is grade I. In terms of specific values, the values of fitness II and fitness I are very close, both of which are negative, indicating that the suitability level of Da'anshan for residential areas has a trend of transforming to level II (Table 7).

## 6. Results and Analyses

**6.1. Decision Results.** Based on the suitability evaluation system constructed and the decision-making model, the suitability evaluation of the reuse modes for eight ACMISs of the Jingxi Coal Mine was obtained (Table 8):

- (1) From the calculation results, the suitability results of Qianjuntai and Muchengjian are similar. The maximum correlation coefficients between Qianjuntai's reuse mode and residential area, park, scientific research and office campus, and commercial service area are  $-0.23$  (III),  $-0.13$  (I),  $-0.18$  (III), and  $-0.18$  (II), respectively. The maximum correlation coefficients between the reuse mode of Muchengjian and residential area, park, scientific research and office campus, and commercial service area are  $-0.27$  (IV),  $-0.06$  (I),  $-0.12$  (II), and  $-0.18$  (II), respectively. They are the most suitable for parks. They are all located near Qianjuntai village, which is one of the first municipal traditional villages in Beijing, so their cultural concentration is far higher than other villages. Their suitability for residential areas is the lowest, mainly because they are located in mountainous areas with large slopes.
- (2) The maximum correlation coefficients of Wangping's reuse model with residential area, park, research office area, and commercial service area are  $-0.12$  (II),  $-0.20$  (III),  $-0.25$  (III), and  $-0.14$  (III), respectively. The suitable grade of the residential area is grade II. The suitability of the commercial service area is grade III, which has the tendency to be transformed to level II. Although Wangping has better economic, environmental, and social conditions than others, Wangping ACMIS has been abandoned for more than 20 years, where the current situation of mine management is very poor, so there is no reuse mode with the suitability of grade I.
- (3) The maximum correlation coefficient of Da'anshan's reuse mode with residential area, park, scientific research and office campus, and commercial service area is  $-0.13$  (I),  $-0.16$  (I),  $-0.10$  (I), and  $-0.03$  (I), respectively. Its suitability level for the four models is I. The calculation results accord with the most superior conditions in all aspects of Da'anshan ACMIS. It is suggested that the reuse project of Da'anshan ACMIS should be given priority.
- (4) The maximum correlation coefficients between the reuse mode of Changgouyu and residential area, park, scientific research and office campus, and commercial service area are  $0.8$  (III),  $-0.09$  (III),  $-0.05$  (I), and  $-0.03$  (I), respectively. Although it is suitable for scientific research and office campus and business service park for grade I but  $-0.03 > -0.05$ . Therefore, a business service park is the best choice for its reuse mode.
- (5) The maximum correlation coefficient of Huapogen's reuse mode with residential area, park, scientific research and office campus, and commercial service area was  $-0.18$  (II),  $-0.05$  (I),  $-0.26$  (II), and  $-0.13$  (I), respectively. The suitable grade for parks and commercial service areas is grade I. Because  $-0.05 > -0.13$ , the park is the best choice.
- (6) The maximum correlation coefficients of Anjiatan's reuse mode with residential area, park, scientific research and office campus, and commercial service area are  $-0.19$  (III),  $-0.01$  (IV),  $-0.20$  (III), and  $-0.23$  (III), respectively. Compared with other research objects, it has lower suitability for the four types of reuse patterns. It shows that it is necessary to explore alternatives to these four reuse modes for Anjiatan.
- (7) The maximum correlation coefficients of the reuse mode of Datai with residential area, park, scientific research and office campus, and commercial service area are  $-0.16$  (II),  $-0.08$  (I),  $-0.04$  (I), and  $-0.26$  (III). The suitable grade of the park and the scientific research and office campus is grade I, especially for the scientific research and office campus. If Jingxi Coal Mine is regarded as a whole, Datai ACMIS is located in the center of all research objects. In addition, as Datai stopped production in early 2021, all of its facilities are preserved in the most complete way. Its underground space without being sealed has high value for scientific research and education. Therefore, it is the best choice to reuse the platform as scientific research and office campus.

**6.1.1. Discussion and Analysis.** The reuse of abandoned mines has always been one of the hot research topics in the academic circle, especially the decision-making of the reuse mode. Different reuse models need to examine different evaluation factors. At present, most similar studies choose a set of evaluation systems to solve the decision-making problems of different reuse modes. In addition, the choice of calculation method is not objective enough to solve the conflict of

TABLE 6: Correlation degree and weight of reusing Da'anshan ACMIS as a residential area.

Index	Correlation degree $K(x)$				Assessment result	
	I	II	III	IV	Level	Weight
Site slope	-0.34	0.45	-0.30	-0.58	II	0.15
Geological hazard risk	0.5	-0.5	-0.67	-0.97	I	0.23
Heavy metal pollution	-0.22	0.4	-0.11	-0.65	II	0.09
Ecological sensitivity	-0.66	-0.58	-0.15	0.15	IV	0.03
Polluted wind	0	0	-0.5	-0.67	I	0.04
Water cleanliness	-0.5	-0.25	0.5	-0.25	III	0.09
Noise level	-0.25	0.5	-0.25	-0.5	II	0.02
Public transportation coverage	0.1	-0.90	-0.95	-0.96	I	0.02
Municipal facilities coverage	0.5	-0.5	-0.75	-0.83	I	0.03
Distance from district center	-0.44	-0.37	-0.29	0.29	IV	0.01
Proportion of tertiary industry	0.23	-0.23	-0.49	-0.62	I	0.01
Real estate development investment	0.21	-0.21	-0.60	-0.74	I	0.06
Public service accessibility	-0.88	-0.76	-0.51	0.49	IV	0.02
Population distribution	-0.43	0.23	-0.18	-0.45	II	0.07
Commercial concentration	-0.41	-0.33	-0.16	0.16	II	0.03
Construction adaptability potential	-0.25	0.5	-0.25	-0.5	II	0.01
Construction engineering stability	-0.25	0.5	-0.25	-0.5	II	0.02
Government or corporate preferences	-0.83	-0.75	-0.5	0.5	IV	0.08

TABLE 7: Comparison and analysis results of reuse modes of Da'anshan ACMIS.

Evaluation object	Reuse mode	Suitability rating				Level
		I	II	III	IV	
Da'anshan ACMIS	Residential area	-0.13	-0.15	-0.35	-0.51	I
	Park	-0.16	-0.28	-0.25	-0.51	I
	Scientific research and office campus	-0.10	-0.13	-0.43	-0.60	I
	Business district	-0.03	-0.17	-0.31	-0.56	I

evaluation index. Therefore, this paper establishes different evaluation index systems for different reuse modes. And the matter-element model that can solve the problem of different kinds of data conflict is used for calculation. This makes the evaluation results more objective than similar studies.

After 2010, the reuse of ACMISs in western Beijing has been continuously in progress. Survey results show that the initial reuse goal for each object is consistent with the decision-making results obtained in the present study (Table 9), indicating that the decision-making method in this paper is feasible, and the evaluation results are reliable. However, the current reuse modes are still dominated by parks, and the selection of reuse modes is relatively simple. Our results confirm that the suitability levels for reusing the Da'anshan, Changgouyu, Datai, and Huapogen ACMISs are all high for various modes, suggesting the feasibility of the multidimensional compound reuse modes.

The results show that this study can assist the government to promote the planning project of coal mine wasteland reuse and enrich the diversity of coal mine wasteland reuse mode. The quantitative analysis of this paper shows that some research objects may be more suitable to be reused as multifunctional comprehensive parks, rather than the single functional park currently planned. These decisions will help promote the smart construction of the city and the intensive use of land and alleviate the severe problem of large population and less land in Beijing.

Finally, it should be pointed out that there are many complex and systematic factors influencing the ACMIS reuse mode decision and cover a large range of disciplines. In future research work, the related theories need to be extensively explored, and the types of reuse modes need to be further refined and expanded.

TABLE 8: Decision-making results for four reuse modes of Jingxi ACMISs.

Evaluation object	Reuse mode	Comprehensive suitability $M$				Level
		I	II	III	IV	
Qianjuntai	Residential area	-0.39	-0.45	-0.23	-0.33	III
	Park	-0.13	-0.45	-0.20	-0.21	I
	Scientific research and office campus	-0.19	-0.26	-0.18	-0.29	III
	Business district	-0.28	-0.18	-0.33	-0.26	II
Muchengjian	Residential area	-0.43	-0.39	-0.33	-0.27	IV
	Park	-0.06	-0.18	-0.27	-0.32	I
	Scientific research and office campus	-0.33	-0.12	-0.26	-0.18	II
	Business district	-0.40	-0.18	-0.37	-0.22	II
Wangping	Residential area	-0.29	-0.12	-0.22	-0.29	II
	Park	-0.22	-0.25	-0.20	-0.21	III
	Scientific research and office campus	-0.33	-0.35	-0.25	-0.26	III
	Business district	-0.27	-0.28	-0.14	-0.37	III
Da'anshan	Residential area	-0.13	-0.15	-0.35	-0.51	I
	Park	-0.16	-0.28	-0.25	-0.51	I
	Scientific research and office campus	-0.10	-0.13	-0.43	-0.60	I
	Business district	-0.03	-0.17	-0.31	-0.56	I
Changgouyu	Residential area	-0.20	-0.40	0.8	-0.49	III
	Park	-0.35	-0.28	-0.09	-0.36	III
	Scientific research and office campus	-0.05	-0.17	-0.30	-0.60	I
	Business district	-0.03	-0.29	-0.25	-0.60	I
Huapogen	Residential area	-0.32	-0.18	-0.35	-0.24	II
	Park	-0.05	-0.32	-0.43	-0.35	I
	Scientific research and office campus	-0.42	-0.26	-0.51	-0.39	II
	Business district	-0.13	-0.26	-0.19	-0.43	I
Anjiatan	Residential area	-0.34	-0.35	-0.19	-0.21	III
	Park	-0.50	-0.34	-0.26	-0.01	IV
	Scientific research and office campus	-0.22	-0.39	-0.20	-0.35	III
	Business district	-0.30	-0.48	-0.23	-0.32	III
Datai	Residential area	-0.31	-0.16	-0.22	-0.30	II
	Park	-0.08	-0.42	-0.46	-0.41	I
	Scientific research and office campus	-0.04	-0.42	-0.41	-0.51	I
	Business district	-0.28	-0.29	-0.26	-0.41	III

TABLE 9: Reuse project of ACMISs in western Beijing.

Name	Reuse intention	Project progress	Reuse mode with high suitability level
Qianjuntai	Aboveground park and underground popular science	Early planning	Park
Muchengjian	Ski park	Early planning	Park
Wangping	Senior housing	No progress temporarily	Residential area
Da'anshan	National mountain sports resort park	Early planning	Park/scientific research and office campus/ business district
Changgouyu	Big data research campus	Early planning	Scientific research and office campus/business district
Huapogen	—	Land reclamation	Park/business district
Anjiatan	—	Land reclamation	—
Datai	Ecopark	Planning is complete	Park/scientific research and office campus

## 7. Conclusion

Although the ACMIS reuse project in western Beijing has been on the agenda, progress is relatively slow at present, and the reuse details need to be further defined. Choosing an appropriate reuse mode is crucial to the sustainable development of an ACMIS. In this study, the appropriate decision-making schemes of four reuse modes of ACMISs in the suburbs of Beijing were explored, based on the EES conceptual framework and the matter-element model. The main conclusions are as follows:

- (1) At the theoretical and methodological level, the method employed in this paper avoids excessive interference from human factors and improves the distinguishability among schemes. Evaluation results obtained from the model not only extract the optimal reuse mode but also suggest alternative reuse modes, which can assist in making objective and reasonable decisions. The results show that the optimal reuse mode for the Qianjuntai, Muchengjian, and Huapogon ACMISs is the reuse as a park, that for Da'an Shan and Changgouyu ACMISs as the business district, that for the Datai ACMIS as the scientific research and office campus, and that for Wangping ACMIS as the residential area.
- (2) A quantitative description method of a qualitative index is provided. The architectural and cultural factors in the evaluation system can only be described by qualitative language, while the extension model must be calculated by quantitative numbers. Therefore, a quantitative transformation method is proposed to assign the qualitative indicators from low to high with four intervals of 0~2, 2~4, 4~6, and 6~8. This method not only ensures the integrity of the index system but also provides an operational way for the quantitative transformation of qualitative indicators.

In the future, the decision-making research on the reuse of abandoned industrial sites in coal mines needs to increase the types of reuse modes and enrich the diversity of mode selection. At the same time, we need more accurate data in the selection of indicators. In addition, the comparative study of various calculation methods is also essential.

## Data Availability

Relevant data and data sources are available within the paper.

## Conflicts of Interest

The authors declare no conflicts of interest.

## Authors' Contributions

Conceptualization was performed by Xiao-Dan Li, Zhi-Ting Chen, and Hao Yang; methodology was conducted by Zhen Liu and Zhi-Ting Chen; software was provided by Zhen Liu;

validation was done by Zhi-Ting Chen, Zhen Liu, and Xiao-Dan Li; formal analysis was performed by Zhi-Ting Chen; investigation was carried out by Zhi-Ting Chen, Hao Yang, and Zhen Liu; resources were provided by Xiao-Dan Li and Zhi-Ting Chen; data curation was carried out by Zhen Liu and Zhi-Ting Chen; original draft was prepared by Xiao-Dan Li and Zhi-Ting Chen; reviewing and editing were carried out by Zhi-Ting Chen; visualization was done by Zhen Liu; supervision was conducted by Xiao-Dan Li and Zhi-Ting Chen; project administration was done by Xiao-Dan Li and Zhi-Ting Chen; and funding acquisition was performed by Xiao-Dan Li.

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