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Analysis of space resources characteristics and transformation paths of mine closure in China

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Abstract

The closure of mines in the coal industry has caused a certain degree of waste of resources, low utilisation rate of resource transformation, and damage to the ecological environment. China is planning to close a substantial number of mines by 2030. Direct closed mines will not only cause huge waste of resources and loss of state-owned assets, but also may include ecological and environmental problems. Main research contents of this paper: (1) Analysed the definition of mine closure and compared the transformation and paths of closed mines in China and abroad. The aboveground transformation paths included mine parks, mine museums, industrial relics, and the utilisation modes of underground space resources mainly include underground storage, underground laboratories, and energy development. (2) used coordinated air-sky-ground multi-source data, divided the types of above/underground resources in the mine, and gave the calculation methods of aboveground buildings space, underground roadways and shafts space, and the estimation methods of underground residual coal resources amount. built a constraint factors system of transformation of closed/abandoned mines. (3) Taked the closed coal mine of Zhujiahe in Shaanxi Province as an example, used the up/down shaft space resource evaluation model, the volume of the buildings was 104,000 m^3, the volume of underground space including shafts, roadways, chambers, and underground car yard is 118,000 m^3, and the total amount of residual coal resources was nearly 56 million tonnes (Mt). Three transformation paths considered for the Shaanxi Zhujiahe coal mine by comprehensive calculation results, mine transformation suitability evaluation, development and utilisation planning scheme. Through the comprehensive benefit evaluation, the optimal transformation path of the mine was determined as aboveground mine park and underground mine museum. The research on the transformation and utilisation of closed/abandoned mine resources can provide new solutions and sustainable development for closed mine enterprises, which is of great significance to reduce the waste of resources and implement China's 'dual carbon' strategic goal.

Keywords: *mine closure, resource types, mine underground space estimation, transformation suitability, development utilisation mode*

1 Introduction

Mineral resources constitute a fundamental material foundation for human survival, and their exploration and utilisation significantly contribute to the advancement of human society (Xi et al. 2020; Zou et al. 2021). Simultaneously, mineral mining also engenders negative impacts, including disruptions to geological and geomorphological conditions, degradation of natural landscapes, and risks to human settlements in terms of safety (Feng et al. 2021; Morris et al. 2005; Zhang & Xi 2020). In light of resource depletion, high mining costs, measures are being implemented to facilitate mine closure. However, the indiscriminate closing mine not only leads to a certain degree of resource wastage but also triggers new instances of mine-related environmental pollution and geological environmental disasters (Xie et al. 2017b). Industrialized countries and regions place significant emphasis on this matter and have conducted extensive research and practical innovations concerning the transformation, mechanisms, and regulations pertaining to closed or abandoned mines (Bandopadhyay & Packee 2000; Getty & Morrison-Saunders 2020; Monosky & Keeling 2021; Nehring & Cheng 2016).

According to statistics, the global number of closed or abandoned mines exceeded 1 million in 2018 (Huo et al. 2019). These mines are primarily distributed across North America, Europe, South Africa, Australia, and East Asia (Yuan et al. 2018). Countries with well-developed mining industries or advanced underground space development technologies, such as the United States, Canada, and Germany, have been at the forefront of research and practical implementation of mine closure strategies since the mid-20th century (He et al. 2018). Their efforts have proven effective in mitigating the adverse impacts associated with mine closures. In the twenty-first century, the increasing number of closed mines globally, coupled with the growing emphasis on sustainable development, has prompted international organisations and scholars to expand their research and practical efforts in the area of closed mines and transformation paths. Consequently, a substantial body of cases, theoretical frameworks, and legal norms pertaining to the transformation paths of closed or abandoned mines has been amassed (Banks & Banks 2001; Chang & Zou 2014; Liu et al. 2018; Wu & Li 2018).

China is one of the world's largest mining countries. It has proven reserves of up to 148 different types of minerals. Additionally, there are over 80,000 large and medium-sized mining enterprises of various kinds operating within the country (Meng 2011). With the continuous mining activities, certain mines have reached the end of their life cycle. Furthermore, some mines with outdated production capacities are facing closure or abandonment. Since 2005, China has implemented a series of policies aimed at rectifying and standardizing the order of mineral resources development. Due to resource exhaustion and outdated production methods, some mines in China have expedited their closure, leading to a significant increase in the number of closed mines. According to available statistics, in 2020, a total of 428 coal mines in China were closed due to capacity reduction or safety concerns. These closures resulted in the withdrawal of approximately 150 million tonnes per annum (tpa) of coal production capacity (Yuan & Yang 2021). It is expected that by 2030, 15,000 coal mines will be closed in China, and the abandoned underground space will reach 9 billion m^3 (Yuan 2017). The closed mines in China still hold significant resources even after their closure. These resources include approximately 42 billion tonnes (t) of coal, nearly 500 m^3 of unconventional natural gas, around 7.2 m^3 of underground space resources, as well as abundant mine water resources, geothermal resources, and tourism resources (Yuan & Yang 2021). The direct closure/abandonment of mines will cause huge waste of resources and loss of state-owned assets (Feng et al. 2013). In the 75th session of the UNGA in 2020, China pledged to strive for carbon peaking by 2030 and carbon neutrality by 2060. Under the background of low-carbon, green, and sustainable development, as well as the principles of the circular economy, the scientific development and utilisation of closed mine resources, along with the promotion of the transformation of mining areas, have emerged as significant concerns within the global energy and environmental domain. However, in China, there remains a dearth of a unified theory and comprehensive reference examples pertaining to closure mine development, as well as the scientific evaluation and management of surplus resources.

Therefore, this study analysed the various types of above/underground resources within closed mines. It provided quantitative evaluation methods for assessing the aboveground and underground spatial resources of closed mines, as well as estimation methods for residual coal resources. Through a suitability analysis, the appropriate transformation paths for closed mines were determined. Taking a closed coal mine in Shaanxi as a case study, the study compared the development and utilization patterns of closed/abandoned mine resources in major mining countries worldwide and presented the optimal transformation path for the mine.

2 Mine closure definitions

2.1 Mine closure/abandoned mine

In China, 'mine closure' is generally defined as the permanent shutdown of a mine enterprise due to resource depletion, complex geological conditions, macro-control, market impact and business conditions (Hu, ZQ et al. 2005). Furthermore, some scholars equate the concepts of 'mine closure,' 'abandoned mine,' and 'mine shutdown', defining them as 'the destruction or occupation of the original landform resulting from mining activities, leading to the formation of economically valueless lands such as open-pit mines, subsidence areas, spoil heaps, and tailings ponds (Lin, G et al. 2018)'. Abroad, the concept of 'mine closure' is explained by several terms, usually translated as mine closure, abandoned mine, disused mine, shutdown mine and discarded mine etc. among which 'mine closure' and 'abandoned mine' are the most common interpretations. Foreign mining enterprises are mostly open-pit mines, so foreign mine closure studies mainly focus on environmental restoration and land reclamation issues, such as Ecorestoration of the coalmine degraded lands published by Springer define 'mine closure' as 'Mine closure as a process refers to the period of time when the operational stage of a mine is ending or has ended and the final decommissioning and mine rehabilitation is being undertaken (Subodh, KM 2013).'

2.2 Comparison of closed mines' transformation in major mining countries around the world

The transformation paths of closed/abandoned mines at home and abroad are summarized and analysed, mainly including aboveground development and utilisation and comprehensive utilisation of underground space (EdenProject 2021; Liu 2007; Liu 2017; SNOLAB 2021; Surhone et al. 2013). The aboveground development and utilisation modes mainly include mine parks, mine museums, industrial relics, etc., and the underground space development and utilisation modes mainly include underground storage, underground laboratory, energy development, etc. (Figure 1)

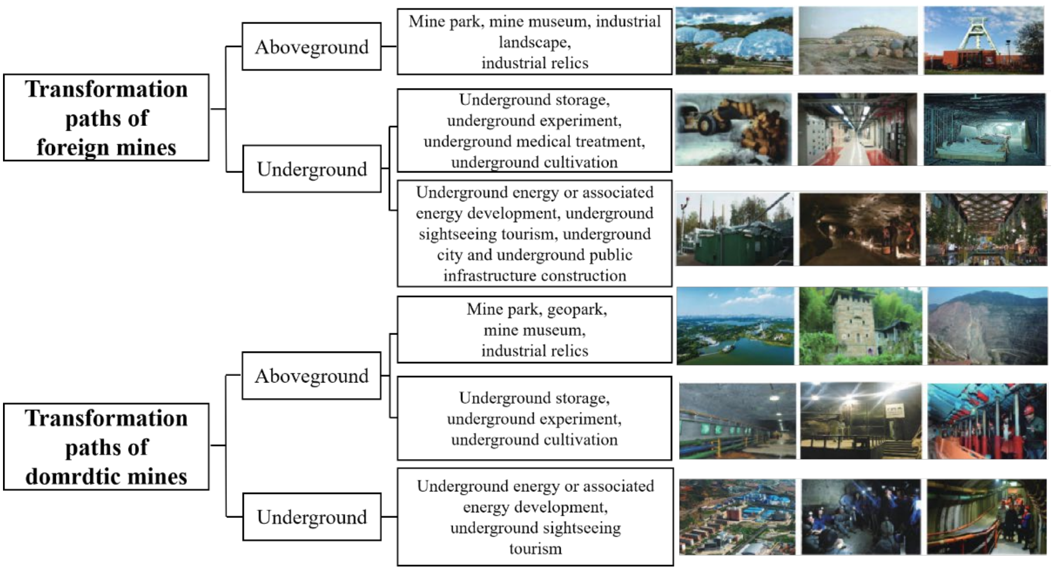


Figure 1 Transformation paths of domestic and foreign closed mines

Developed countries such as the United States and Germany completed their industrialization earlier. These countries paid attention earlier to the problems of industrial transformation, environmental damage, and waste of resources by closing mines, and carried out the exploration of multi-path mine closure transformation according to local conditions. For example, American Kansas transformed mine tunnels into storage rooms, factories and offices (Vitt & Kjelshus 1980); Louisville used underground giant caves as storage warehouses, as well as tourist attractions and activity center (Ullrich et al. 1984); The city of Bochum in the Ruhr area of Germany has utilized abandoned industrial sites to establish museums and undertake underground tourism and recreational activities (Lauderbach 2012). Among these cases, the use of underground space is the main mode of mine development and utilisation (Sterling et al. 2012). China started its industrialization process relatively late, but it has also made significant efforts in the transformation of closed/abandoned mines (Dong et al. 2021; Wang ＆Ren 2003). The more famous ones are the Pan'an Lake in Xuzhou city and the 'Deep Pit Hotel' in Shanghai. In addition, Shendong Mining Area has successfully built underground reservoirs, leading the world. The reuse of potential energy in closed/abandoned mines and the underground storage of various items have also made progress in China. The underground aquaculture technology is simpler than other transformation methods, and there are successful cases at home and abroad. However, there is still a certain gap in the development of new industries such as underground experiments, underground medical treatment, underground cities, and public infrastructure construction in China compared with foreign countries. In the future, it is necessary to develop a new direction for the transformation and utilisation of diversified closed mines, and accelerate the green and sustainable transformation of closed mines (Xie et al. 2017a; Yuan 2021).

3 Type identification and spatial characteristics of closed/abandoned mine resources

3.1 Mine resources identification based on multi-source data

Based on the analysis of remote sensing images, the selection of the UAV flight site and target area was performed. Flight operations were then carried out on the designated target area to obtain a panoramic view of the mining area (Figure 2). Subsequently, the aerial data captured by the UAV was stored, transferred, and analysed. This analysis involved various processes to classify the ground resources within the mining area. By utilising high-resolution remote sensing images and low-altitude UAV data, we can identify various resources on the ground within the mining area based on the characteristics of the industrial site. These resources include surface water, unused land, industrial squares, and buildings in residential areas.

According to the mine hydrogeological data, the mine production geological data, the fully mechanised face mining data, design drawing of fully mechanised mining face, mining engineering plan, equipment retracement of working face and other data, the types of underground resources of the mine are identified, including groundwater resources, residual coal resources, underground space resources, and underground equipment. The layout of the underground roadway is shown in Figure 3.

Figure 2 UAV aerial panorama

Figure 3 Layout of underground roadway

3.2 Types and characteristics of closed/abandoned mine resources

The resources in closed/abandoned mines are generally divided into aboveground and underground resources (Figure 4). The surface water resources of a mine mainly refer to ponds, rivers, lakes, reservoirs and other water bodies around the mining area. The idle land resources include abandoned land and subsidence area caused by mining. The industrial square of the mining area mainly includes buildings and structures (office buildings, dispatching buildings, wellhead buildings, coal preparation plants, power and auxiliary facilities, etc.), and ground linear facilities (railways, highways, power and communication lines, etc.). The ground equipment mainly inclu des equipment for lifting, transportation, ventilation, drainage, power supply, compressed air, coal preparation, etc. The living area meets the living requirements of the mine workers and generally consists of buildings for welfare, culture and education, sanitation, commerce and residence.

The groundwater resources in mines include water from bottom sump, goaf water, and underground water in the water system where the mine field is located. The residual coal resources mainly include the unexploited coal seam and the protective coal pillars at the main roadway, shaft, working face, fault and boundary of mine field. The underground space of mine mainly includes roadway, chamber, underground car yard and shaft. Underground equipment is mainly various types of equipment with low value and large volume that are difficult to withdraw to the surface. The purpose of dividing mine resources is to guide mine transformation according to the characteristics of mine resources, so that the transformation can be more in line with the local reality. When formulating the transformation paths of the mining area, the location, degree of regional economic development, scale of the minefield, service life of the mine, surface runoff, age of the buildings, underground space volume, and the residual coal resources should also be considered.

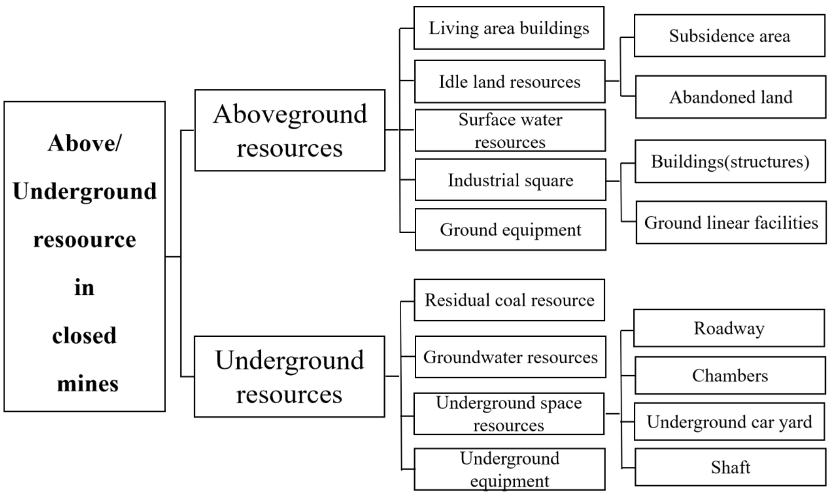


Figure 4 Types of above/underground resources in closed mines

4 Estimation of above/underground space resources in closed/abandoned mine

Among the residual resources of closed/abandoned mines, the aboveground industrial square space resources, underground space resources and residual coal resources are the most important resources and have great utilisation value. Therefore, these resources are quantitatively evaluated. Other resources such as above/underground residual equipment resources can be counted according to the mine closure retracement data, the aboveground and underground water resources can be estimated by river flow, lake or reservoir water storage, and groundwater level, and the land resources can be measured and counted.

4.1 Estimation of building space of industrial square

Generally, abandoned industrial square is not affected or is less affected by coal mining, with good engineering, geological conditions and complete transportation, power supply, water supply, gas supply and other facilities, which can be directly planned and utilised. For the available space of the buildings of the industrial square, it can be calculated according to Formula 1 and 2.

$$S_{buil} = \sum_{i=1}^{n} L_{buil} \times D_{buil} (i = 1, 2, 3, \ldots, n) \quad (1)$$

$$V_{buil} = \sum_{i=1}^{n} L_{buil} \times D_{buil} \times H_{buil} (i = 1, 2, 3, \ldots, n) \quad (2)$$

Where： S_{buil} is the floor area of the building, m^2; L_{buil}, D_{buil} and H_{buil} are the length, width and height of the building respectively, m; V_{buil} is the available space of the building, m^3.

4.2 Quantitative assessment method of underground space resources

4.2.1 Estimation of underground space

4.2.1.1 Underground roadway, chamber and underground car yard

The space shape of chamber and underground roadway is similar, and the underground car yard of the mine is a combination of multiple underground roadways, so the spatial calculation methods of the three are similar. Taking the underground roadway as an example, the cross-sectional shape of the roadway mainly includes semicircular arch, circular arch and trapezoid, and the shape rules are shown in Table 1 (Tang 1996). The space of different types of underground roadways can be calculated according to formula 3.

$$V_{rway} = \sum_{i=1}^{n} S_{rway} \times L_{rway} (\mathrm{i} = 1, 2, 3, \ldots, \mathrm{n}) \quad (3)$$

Where: V_{rway} is available space of roadway, m^3; S_{rway} is the net sectional area of roadway, m^2; L_{rway} is the length of roadway, m.

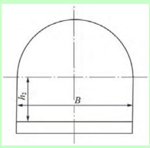
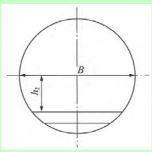
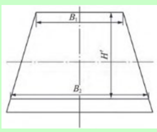
4.2.1.2 Shaft of coal mine

The available space of shaft can be calculated according to formula 4:

$$V_{shaft} = \sum_{i=1}^{n} S_{shaft} \times H_{shaft} \, (i = 1, 2, 3, \ldots \ldots, n) \quad (4)$$

Where: V_{shaft} is the available space of shaft, m^3; S_{shaft} is the net sectional area of shaft, m^2; H_{shaft} is the height of shaft, m.

Table 1 Different types of roadway specifications and section calculation

Types of roadway	Section shape	Net section area calculation formula	
Semicircular arched roadway		S_1=B(0.39B+h_2)	S_1: Net sectional area of semicircular arched roadway B: Net roadway width h_2: Height of roadway wall from the ballast surface
Circular arched roadway		S_2=B(0.24B+h_2)	S_2: Net sectional area of circular arched roadway B: Net roadway width h_2: Height of roadway wall from the ballast surface
Trapezoidal roadway		S_3=0.5(B_1+B_2)H	S_3: Net sectional area of trapezoidal roadway B_1: Net width at the top beam of the roadway B_2: Net width at the bottom of the roadway H: Height after the roadway is deformed and stabilized

4.2.2 Estimation of underground residual coal resources

The residual coal resources mainly include unexploited coal seam and protective coal pillars, among which the amount of unexploited coal seam resources can be obtained from the mine closure data. The protective coal pillar refers to the coal seam within the mine field that has not been mined to ensure the stability of ground buildings, railways, water bodies or safe production of mines, such as the protective coal pillar reserved in a certain range of the corresponding underground for the protection of surface railways, bridges, towns and villages. There are three calculation methods of protective coal pillar, including vertical section method, vertical line method and digital elevation projection method, among which vertical section method is the most commonly used (Wei et al. 2008). According to the vertical section method, the amount of the protective coal pillars is calculated (Xu et al. 2015). The specific calculation method is shown in Formula 5.

$$M = \sum_{i=1}^{n} A \times H \times v(i = 1, 2, 3, \dots\dots, n) \quad (5)$$

Where: M is the estimated coal pillars resources, tonne; A is the land area occupied by the coal pillar (coal seam dip is considered horizontal), m^2; H is the thickness of the coal seam, m; η is the bulk density of coal, t/m^3.

4.3 Suitability study on the transformation direction of closed/abandoned mines

Different transformation paths of closed/abandoned mines require mines to meet different resource requirements. Underground storage has high requirements on the depth and geological structure of the mine. When storing industrial waste such as radioactive waste, it is also necessary to consider whether there will be physical and chemical reactions between radioactive waste and the surrounding environment (Peila ＆ Pelizza 1995). The development of underground energy and its associated resources should not only consider the mine's own resource occurrence and geological conditions, but also consider the market orientation (Li et al. 2013). Closed mines with good environmental quality, convenient transportation, complete infrastructure and close to mature scenic spots should take the leisure and vacation path as the transformation direction. The transformation and development direction of the closed mining area where the coal mining subsidence area is prone to accumulation of water should focus on wetland restoration. The vegetation restoration model is the first choice for abandoned mining areas with poor geographical location, poor reclamation conditions, no tourism value on the ground, and difficulty in building artificial landscapes. Therefore, it is necessary to evaluate the suitability before formulating the development and utilisation mode of closed mines. The transformation constraint factors of closed mines are proposed, as shown in Figure 5. The constraint factors mainly include four aspects: mine resource conditions, natural conditions, external factors and economic feasibility. Mine resource conditions include mining methods, resources and facilities, mine type, transformation potential and mine size. Natural conditions include surface subsidence, soil erosion, surrounding rock conditions, pollution conditions and mining depth. External factors include location conditions, public support, market demand, technical demand and policy completeness. Economic feasibility includes industrial structure, economic share, mining output value, number of employees and economic growth rate.

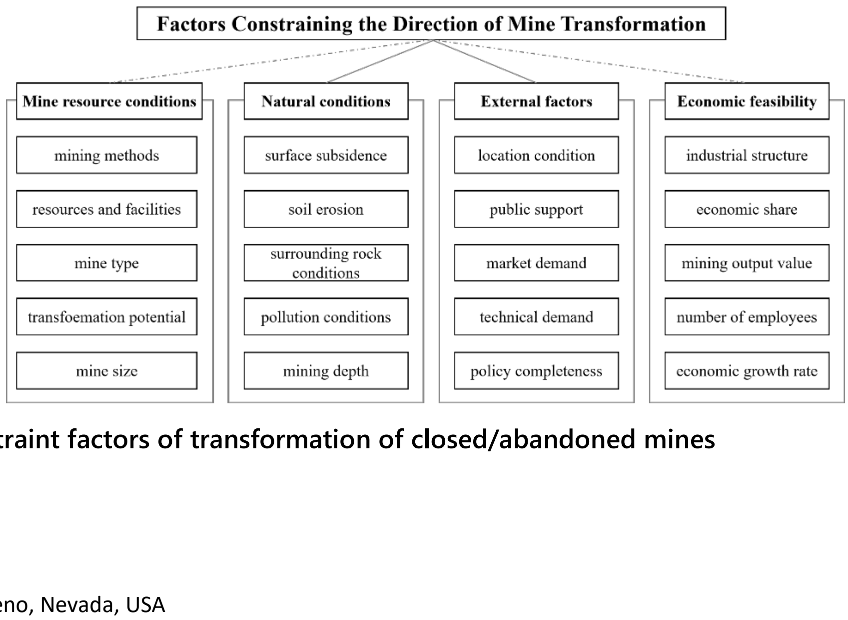


Figure 5 Constraint factors of transformation of closed/abandoned mines

According to the characteristics of mine resources and referring to the relevant specifications such as the 'Engineering Rock Mass Grading Standard (GB/T 50218-2014)', 'Water Conservancy and Hydropower Engineering Geological Survey Specifications (GB 50487-2008)' and 'Soil Erosion Classification and Grading Standard (SL190-2007)', the expert scoring method is used to score the constraint factors of the mine transformation. According to the scoring results of each constraint factor, the potential resource advantages of the closed mines in some aspects are summarised. Based on this, various transformation paths of the closed mine are initially put forward. Then, the optimal mode of the mine is determined through the comprehensive benefit evaluation, and the specific transformation scheme planning and design of the mine is carried out. The steps for determining the transformation path are shown in Figure 6.

Figure 6 Steps to determine the transformation path of closed/abandoned mines

5 Development and utilisation modes of closed mines: A case study of transformation of a closed mine in Shaanxi, China

The closed mine is located in Baishui County, Weinan City, Shaanxi Province. Baishui County has Fangshan Forest Park, the largest artificial forest farm in Shaanxi, Lingao Lake, one of the ten largest lakes in Shaanxi, and 36667 hm^2 of apple resources, which has great potential for tourism development (Government 2022b). The Lingao Lake tourist area is to the west of the mine, and an apple planting base of 667 hm^2 is in the north. The Han (Jing) Dong (Po) Railway (coal transportation line) runs through the middle of the mine, and railway station is built. The highway and railway transportation in and around the mine area is very convenient. The method of inclined shaft development is adopted by the mine, and the strike longwall mining method is adopted for coal mining. In 2012, the production capacity of the mine was verified to be 1.8 million tpa. In 2016, the mine was closed, all shafts and wellhead rooms were closed, and all kinds of buildings (structures) in the mine are idle and have not been used.

5.1 Characteristics of above/underground space resources of the closed mine

5.1.1 Aboveground space resources

After the closure of the mine, there is no obvious deformation on the surface, the buildings are well preserved, and the basic supporting facilities are complete. The length, width and height of buildings in the mine are measured on site, and the floor area and space volume of the buildings are calculated according to formulas 1 and 2. The final approximate results are shown in Table 2.

Table 2 General situation of aboveground space resources in a closed mine in Shaanxi, China

Types of aboveground space resources	Floor area(m^2)	Space volume(m^3)
Office buildings (administrative office building, garage, office laboratory, etc.)	2,375	22,000
Living area building (dormitory buildings, staff canteens, gym, etc.)	5,074	34,000
Production area buildings (main transformation room, machine repair plant, warehouse, etc.)	5,696	38,000
Auxiliary production area buildings (circular coal storage yard, water treatment sedimentation tank, sewage treatment room, etc.)	9,951	10,000
Total amount	23,096	104,000

5.1.2 Underground space resources

The underground engineering of the mine is completely stagnant and the geological risk is low. The underground space of the mine mainly includes main and auxiliary inclined shafts, transportation roadway and returning air roadway at first level, mine underground car yard, central water pump house and passage, material depot and other chambers. The total space volume of the buildings in the mining area is 104,000 m^3. The total available underground space in the mine is 118,076 m^3 according to formulas 3 and 4 (Table 3).

5.1.3 Underground residual coal resources

A total of 42 working faces were operated in four mining areas of Zhujiahe Coal Mine. The main mining methods employed were blasting and comprehensive mechanized mining. The coal seam thickness for the mining operations was 2.6 meters, the protective coal pillars with a width of 20-40 m are left between the working faces, and the bulk density of the coal is 1.40 t/m^3. According to formula 5, the remaining coal pillar resources at the working face are about 1.441 Mt (Table 4). The amount of unminable coal resources in the mining area due to railways, rivers, reservoirs, faults, mine field boundaries, roadways, return air wells, industrial squares and villages is 55.15 Mt. The total residual coal resources in the mine are calculated to be nearly 56 Mt. As most of the underground residual coal resources of the coal mine are protective coal pillars, it is difficult to develop and utilise with the current technical level. For the large-area non protective coal pillar residual coal resources existing in other closed mines, underground coal gasification can be considered for development and utilisation.

Table 3 Overview of underground resources

Types of underground space resources	Area (m^2)	Length (m)	Volume (m^3)
Main inclined shaft	11.1	820	9,102
Auxiliary inclined shaft	12.2	561	6,844
Transportation roadway at first level	12.3	3,298	40,565
Returning air roadway at first level	12.3	3,298	40,565
Mine underground car yard and main chambers	-	-	21,000
Total amount	-	-	118,076

Table 4 Residual coal resources

Working face	Width (m)	length (m)	Coal (tons)
A-B	20	4,492	327,000
C-D	25	3,948	359,000
E-F	30	4,277	467,000
G-H	35	1,052	134,000
I-J	40	1,061	154,000

5.2 Proposal of development and utilisation modes of the closed mine

The mine has beautiful environment, superior geographical location, complete infrastructure and supporting facilities, and there are many mature scenic spots around it. The transformation and utilisation of the mine is in line with the requirements of mining tourism development. Taking mining tourism as the new economic growth direction of the mining area is of great significance to the economic diversification and sustainable development of mining towns. According to the preliminary evaluation of the suitability of the mine transformation, three transformation paths are put forward.

Frist, Transformation into mine park or resort mode (mode 1). The internal facilities of the mining area are complete, and there are scenic spots in the surrounding area, with superior geographical position and convenient transportation. This transformation path can not only reflect the history of mining development, but also protect industrial relics. Second, Transformation into mine park or mine museum (mode 2). The mining area has rich industrial relics and cultural history, and the equipment in the mining area is well preserved, which can transform the mining area into a mode integrating mine park and mine museum, with research value and educational function. Third, Transformation into mine museum or underground material reserve (mode 3). The underground space of the mining area is large. Using the special nature of the mine, the underground space of the mine can be built into an underground greenhouse to store and preserve vegetables and fruits, breed special animals and plants, or store special substances. It can also be used for underground reservoir construction and mine groundwater storage. At the same time, the mine museum will be developed to organically integrate the aboveground and underground spaces to effectively promote the transformation of mining areas.

5.3 Comprehensive benefit of development and utilisation modes of the closed mine

The transformation paths of the closed mine are not singular, and the comprehensive benefit maximisation is the criterion for mode selection. The benefits of mine transformation refer to the various benefits generated in the process of recycling and making full use of closed mine resources according to local conditions, which can be divided into three parts: economic benefit, ecological benefit and social benefit. The economic benefits brought about by the transformation of mines mainly come from industrial and cultural tourism. Therefore, the main indicators for measuring economic benefits are: government subsidies, ticket revenue of tourist attractions, and catering revenue of the catering industry. Ecological benefits refer to the improvement of ecological environment quality, mainly in the aspects of water and soil conservation, water purification, and environmental purification. Social benefits are the social effects and influences produced by certain social activities, which are indirect benefits and cannot be directly quantified. There are three main aspects to measure social benefits: expanding employment, improving the image of the city, and improving the level of development. The comprehensive benefit brought by the three transformation paths of the mine were analysed by using the evaluation index system of comprehensive benefit of mine transformation, in order to find the optimal transformation scheme.

5.3.1 Comprehensive benefit of evaluation index system for mine transformation

The comprehensive benefit of evaluation index system for mine transformation consists of three parts (Figure 7). The first part is the target layer (D), which reflects the level of comprehensive benefits of mine transformation. The second part is the criterion layer (P), including ecological benefit index P1, social benefit index P2 and economic benefit index P3. The third part is the index layer (A), which contains nine descriptive and evaluation indicators including water and soil conservation a_{11}, water purification a_{12}, environmental purification a_{13}, employment expansion a_{21}, city image improvement a_{22}, development level improvement a_{23}, government subsidies $_{a31}$, ticket revenue a_{32} and catering industry development a_{33}.

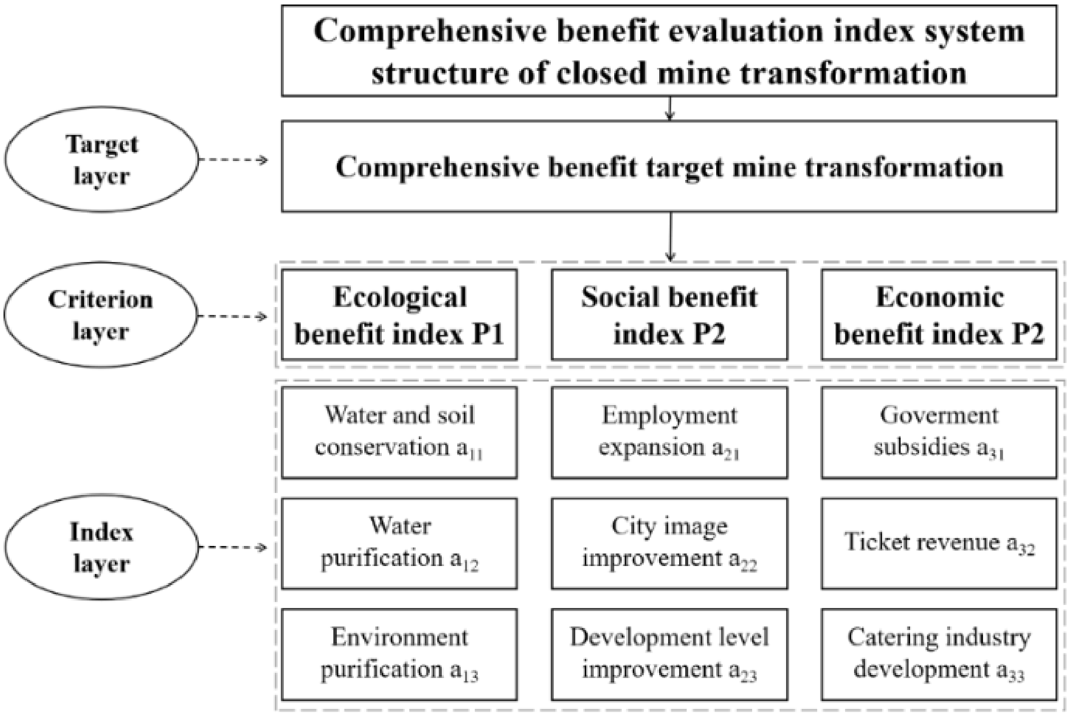


Figure 7 Comprehensive benefit of evaluation index system for mine transformation

5.3.2 Determination of indicators' weight

According to the hierarchical structure of the comprehensive benefit evaluation for mine transformation, the relative importance of each indicator in each level is compared pair-wise to determine the relative importance of the indicator, a judgment matrix is established, and the weight of each indicator is obtained by using analytic hierarchy process and empirical knowledge (Table 5).

5.3.3 Comprehensive benefit result

Each benefit index is difficult to quantify, the expert scoring method is used for data analysis, and the average value is used to describe the specific value of each benefit index. The index weight is multiplied by the index value to obtain the comprehensive benefit values of three transformation modes (Table 5). It can be seen from Table 5 that the comprehensive benefit of mine park or mine museum was the largest, which is 3.748. Therefore, the optimal transformation path for the mine is mine park or mine museum.

Table 5 Weight of evaluation index of comprehensive benefit for mine transformation

Target layer(D)	Criterion layer(P)	Weight	Index layer(A)	Weight	Mode 1	Mode 2	Mode3
Comprehensive benefits	Ecological benefit(P1)	0.1936	Water and soil conservation(a_{11})	0.0516	3.31	3.39	3.52
			Water purification(a_{12})	0.0516	3.20	3.33	3.47
			Environmental purification(a_{13})	0.0627	3.25	3.50	3.52
	Social benefit(P2)	0.3943	Employment expansion(a_{21})	0.1360	3.92	4.01	3.63
			City image improvement(a_{22})	0.0996	3.81	3.92	3.75
			Development level improvement(a_{23})	0.1303	3.63	3.88	3.59
	Economic benefit(P3)	0.4121	Government subsidies(a_{31})	0.1066	3.42	3.53	3.92
			Ticket revenue(a_{32})	0.1994	3.65	3.71	3.41
			Catering industry development(a_{33})	0.1622	3.73	3.85	3.31
Comprehensive benefit					3.623	3.748	3.551

5.4 The most suitable development and utilisation scheme design of the mine

By analysing the comprehensive benefits of the mine transformation, combined with the results of the quantitative assessment of space resources, it is determined that the optimal utilisation mode is the mine park or mine museum. Figure 8 shows the preliminary design for the transformation and utilisation of the mine.

Area A is designated as the living area. It is close to the road in the south, adjacent to the parking lot, office area and ecological green space, which can meet the needs of residents' travel, work and life. Area B is designated as the office area, comprising well-preserved building facilities including administrative and production office buildings. Area C is designated as parking area. Situated on the right side of the entrance to the south gate of the coal mine. Area D is an ecological grassland with abundant woodlands and a central contiguous forest. The open space beneath can serve as a camping zone. Its proximity to the office district and residential zone offers opportunities to enhance plant diversity, expanding the green area for employees' wholesome lifestyle. Area E is assigned as a warehouse, serving as the auxiliary production area for the coal mine. Key structures in this area comprise machine repair workshops and warehouses. The workshop requires demolition, retaining only the concrete and steel framework as an industrial landscape element. Located close to the experimental training base, the warehouse has potential for renovation to facilitate storage of training equipment, thereby improving its functionality. Area F is a designated mine park with infrastructure facilities like power distribution stations and sewage treatment plants. Square ponds are present for sewage treatment, offering opportunities for cultivating various aquatic plants. It boasts lush greenery and diverse plant life, making it suitable for transformation into a park. Adjacent to the sedimentation tank, there is a leisure park. Overall, Area F can be developed into a comprehensive mine park. Area G and H are designated as a mining culture experience hall and museum. They contain abandoned facilities and equipment with a distinctive industrial ambiance. These structures can be restored and utilized, including coal yards, gangue dumps, coal preparation buildings, coal conveying corridors, and coal bunkers. By incorporating modern technologies like multimedia, the renovation process can showcase the mine's century-old history and unique mining culture in a visually impressive way. Area I is designated as a training base, which can be developed after addressing soil pollution. The coal preparation building walls can be converted into rock climbing walls, while the waste dump can become a real-life Counter-Strike (CS) site for tactical training. These adaptations add excitement and diversity to the base while creatively repurposing existing structures.

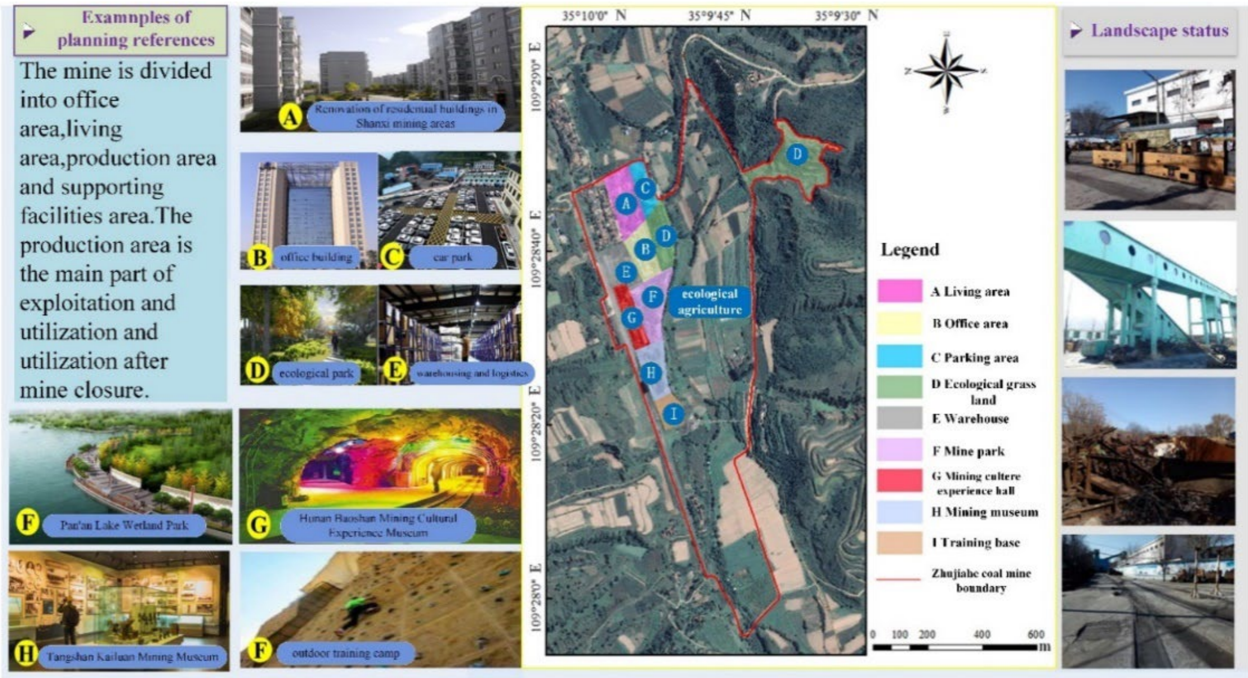


Figure 8 Planning and utilisation map of the mine in Shaanxi, China

6 Conclusion

The closure or abandonment of mines has led to a significant level of resource wastage, a low rate of utilisation in resource transformation, and considerable damage to the ecological environment. Considering the global background of the 'dual carbon strategy', it is urgent to study and explore the characteristics of the above/underground space resources of closed/abandoned mines and the transformation paths of mines. This study presents a comprehensive summary of practical case studies on the transformation paths of closed or abandoned mines in both China and foreign countries. Developed countries, including the United States and Germany, have amassed valuable practical experience in areas such as mining tourism development, underground space utilisation, and associated resource development. They have also pioneered various transformation paths for closed mines. In contrast, the overall transformation of closed mines in China is still in the experimental stage and the transformation paths employed are relatively straightforward. Therefore, there is a need for China to explore new avenues for diversified transformation and utilisation of mines. Based on this analysis, the study categorizes the aboveground and underground resources of closed mines and provides quantitative evaluation methods for assessing the resources in the aboveground and underground spaces of these closed mines. Additionally, estimation methods for residual coal resources are proposed. Furthermore, an appropriateness assessment model for mine transformation is constructed. In addition, the paper selected a closed mine in Shaanxi, China as a case study. The above/underground resources of the mine were quantitatively evaluated, and an optimal transformation paths was proposed based on the evaluation. The study provides a theoretical foundation and methodological reference for quantifying the underground space resources of closed mines. Furthermore, it offers practical and feasible transformation blueprints and reference examples for other closed mine enterprises seeking to achieve transformation, overcome challenges, and ensure sustainable development.

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