Research on brownfield redevelopment based on Wuli-Shili-Renli system theory and catastrophe progression method

He Jian¹, Hu Hao¹*, Pan Haize², Liu Chuan², Li Xiaojin², Wei Yan¹, Jiang Haidan¹, Zhang Changliang¹

¹ School of Civil Engineering, Chongqing University of Arts and Sciences, Chongqing, China, ² School of Civil Engineering and Geomatics, Southwest Petroleum University, Chengdu, China

* hhxkfy@126.com

Abstract

Brownfields are an important part of urban land resources. Strengthening the governance and redevelopment of brownfields is significant to environmental protection, high-quality urban development and sustainable development. However, due to the complexity and harmfulness of brownfield pollution, the hasty, untimely, and blind development can cause serious consequences. It is infeasible to pay more attention to development than governance or vice versa. In this paper, aiming at brownfield redevelopment evaluation, we introduced the Wuli-Shili-Renli (WSR) system methodology, an oriental system thought combining qualitative and quantitative analyses, comprehensively analyzed the influencing factors of brownfields from three dimensions of Wuli, Shili and Renli, and constructed the evaluation index system of brownfield redevelopment. To avoid much subjectivity in the evaluation process, we established the evaluation model of brownfield redevelopment using the catastrophe progression method. Taking the renovation project of Shanghai Xintiandi in 1999–2001 as a reference, the evaluation index system and evaluation model were applied to the renovation project of Wenjia Street in Qingyang District, Chengdu, Sichuan Province, China in 2022, and the results provided a good basis for the decision-making process.

Introduction

Land is the place for human existence and all activities. With the rapid development of society, the pace of industrialization and urbanization is faster and faster. People are gradually aware of the deterioration of the ecological environment while enjoying the good material conditions brought by industrialization and urbanization. In 2014, there were about 4.2 million brownfields in the EU [1]; in 2018, the United States had more than 450,000 brownfields [2]; in 2020, there were about 21,000 brownfields in England [3]. As of 2012, there were about 300,000 brownfields in China, with a total area of about 20 million hectares. With the economic development and the adjustment of urban industrial structure, the number of brownfields is increasing year by year [4]. In 2020, there were more than 7000 brownfield-related plots in
Chongqing, China, covering an area of about 102 million square meters. In 2020, General Secretary Xi Jinping presided over the sixth meeting of the Central Committee for Financial and Economic Affairs and pointed out that we should promote the construction of the Chengdu-Chongqing economic circle, optimize the land spatial layout, strengthen ecological and environmental protection, and promote the high-quality development of the Chengdu-Chongqing region. However, the continuous emergence of brownfields has become the main factor affecting the urban environment and hindering the high-quality development of urban areas [5]. Generally, brownfields have superior geographical locations and great potential development values [6]. However, due to metal pollution, chemical pollution and other pollution generated by original factories in the production process [7], obstacles exist in the redevelopment and utilization, which makes it difficult to fully utilize the traffic advantages and economic benefits of brownfields. In this paper, we will focus on the scientific evaluation system of brownfield redevelopment to provide a reasonable basis for the feasibility decision of brownfield redevelopment.

**Literature review**

In recent years, the social and environmental problems and potential economic benefits of brownfields have attracted increasing attention from researchers. Bieback [8] pointed out that the most effective way to solve the urban housing problem was to develop brownfields. Tiesdell [9] compared the advantages of brownfield housing development with greenfield housing development and proposed that brownfield housing development was the trend. Cao [10–12] put forward constructive suggestions on China’s brownfield issues on the basis of summarizing the experience of foreign brownfield redevelopment. In conclusion, brownfield redevelopment is an important means to solve the problem of land resources.

Currently, few methods are used in brownfield redevelopment research. Guo [13] evaluated the feasibility of brownfield redevelopment schemes using the multi-level grey evaluation method. Fang [14] and Wang [15] performed a fuzzy comprehensive evaluation to evaluate the feasibility of brownfield redevelopment schemes. Ye [16] proposed a strategic classification support system for brownfield redevelopment based on the rough set theory and multi-criteria decision theory and applied it to 201 cities in the United States; the results showed that this system could help BR project planning and budget [16]. Lesage [17] took brownfields in Montreal, Canada, as an example and proposed a modeling framework to evaluate the brownfield management decision based on the whole life cycle theory. Hou [18] used the structural equation model to prove the interests among society, economy, environment, system, stakeholders and brownfield restoration. Although these methods can evaluate the feasibility of brownfield redevelopment well, they all need the weight of each index, having strong subjectivity, complex calculation processes, a large amount of calculation and insufficient applicability. In this paper, the Wuli-Shili-Renli (WSR) system methodology was introduced into the evaluation index system of brownfield redevelopment, and the catastrophe progression method was applied to build a brownfield redevelopment evaluation model. The integration of the both formed a complete brownfield redevelopment evaluation system, and its applicability and rationality were verified in practical cases, which has good directive significance for brownfield redevelopment in China.

**Methodologies**

**Wuli-Shili-Renli system methodology**

As the abbreviation of “Wuli, Shili and Renli”, WSR was proposed by Professor Gu Jifa and Dr. Zhu Zhichang, famous experts in Systems Science in China, at Hull University, UK, in
1994. It is mainly used to solve complex problems [19]. The core of this methodology is to understand the objective reality of things when dealing with complex problems and use knowledge of natural science and humanities and social science to treat things well [20] to study complex problems systematically, completely and hierarchically. It is an oriental system thought combining qualitative and quantitative analysis [21].

The WSR system methodology has been introduced into various research fields [22]. Wang [23] used the WSR method to evaluate the quality of avionics software. Ji [24] used the WSR system methodology to build an intelligent building energy management model and evaluated the establishment of building energy management platforms. Luo [25] used the WSR system methodology to construct an evaluation index system of land expropriation and resettlement for social stability risk. Li [26] constructed a factor system of manufacturing energy intensity based on the WSR system method.

In the WSR system methodology, Wuli refers to the objective existence that people encounter in studying a research object, such as the environment and characteristics of the research object. Shili is the logical method used by people in studying the object, such as relevant policies and measures. Renli refers to people, the relationship among people and the behaviors of people in studying the object, such as the purposes and emotions of people and the distribution of benefits among people [27, 28]. Wuli, Shili and Renli are not independent and distinct from each other but interdependent with each other. They are the analyses of the same thing from different dimensions, which interact with and complement each other. The WSR system methodology focuses on what the system of Wuli, Shili and Renli is without deliberately paying attention to the simplicity or complexity of the problem. The basic idea of the WSR system methodology [29, 30] is shown in Table 1.

T**Table 1. The basic ideas of the WSR system methodology.**

| Category          | Wuli                                      | Shili                                      | Renli                                      |
|-------------------|-------------------------------------------|--------------------------------------------|--------------------------------------------|
| Basic connotation | Appearance of objective things             | Mechanism of things                        | The relationship among people and the relationship among departments |
| Theoretical basis | Physics, laws, rules and norms            | Management theory                          | Principles of ethics, scientific thinking and morality |
| Analysis object   | The objective world, resources and constraints | Organization, system and participation mechanism | Individuals, groups, relationships, people |
| Purpose           | What is it?                                | How to do it?                              | How should it be?                          |
| Principle         | Faithful, correct and objective           | Harmony, efficiency and fair competition    | Humane, effective, flexible and coordinated |
| Required knowledge| Natural sciences                           | Management science, system science and operations research | Human and interpersonal relations, behavioral sciences and social sciences |

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**Applicability analysis of the WSR system methodology for brownfield redevelopment**

Brownfield redevelopment involves pollution control, financial management, environmental remediation, system management, laws and regulations, etc. Due to the complex work, the project management method of brownfield redevelopment research should meet the requirements of risk assessment, sustainability and economic benefits. In this paper, we introduced the WSR system methodology into the evaluation index system of brownfield redevelopment. The WSR system methodology can comprehensively analyze the feasibility of brownfield redevelopment from Wuli, Shili and Renli to avoid neglecting key factors and effectively improve the developers’ understanding of brownfield redevelopment. In addition, it can improve the level of brownfield redevelopment management by coordinating the relationship among the three dimensions.
Through applying the WSR system methodology, according to the three dimensions of Wuli, Shili and Renli, we analyzed the decision-making management of brownfield redevelopment from six aspects, including brownfield pollution control, brownfield geographical conditions, policy support, capital investment, investment income, and information orientation, and formulated a reasonable development plan to achieve the expected decision-making objectives. Combined with the evaluation system of the WSR system methodology (Fig 1), we re-divided the evaluation index factors, enhanced the cognition of the relationship among the indexes, accurately evaluated the key evaluation indexes, and comprehensively improved the reliability of the evaluation index system of brownfield redevelopment.

Analysis of the evaluation model of brownfield redevelopment based on the WSR system methodology

In the brownfield redevelopment evaluation system, the objective material conditions and theoretical basis in the evaluation process are supported by the Wuli dimension. Wuli is the implementation of the evaluation process, which provides a theoretical basis for Shili and a principle of communication and coordination for Renli. The Wuli dimension and the Shili dimension complement each other. The Shili dimension is combined with the objectives of the evaluation system to formulate practical and efficient policies, fund-use plans, measures and specific implementation principles, restrict the Wuli and Renli dimensions, ensure the existence form of Wuli, determine the inter-organizational relationship of the Renli dimension, and then apply effective policies, measures and principles to ensure the reliability of the evaluation system. The Renli dimension consists of various organizational relationships, interpersonal relationships and cognitive relationships; the learning of Wuli improves the cognition of brownfield redevelopment; the principle of Shili restricts the objective reality of brownfield redevelopment evaluation and ensures the operation of the evaluation system.

In applying the WSR system methodology to evaluate brownfield redevelopment, the Wuli dimension is used as the objective learning and cognitive basis, the policies and principles of
the Shili dimension as the constraint method, and the Renli dimension as the core. The three dimensions coordinate with each other and jointly promote the brownfield redevelopment evaluation to ensure the smooth evaluation process and lead to reliable evaluation results. The relationship among the three dimensions is shown in Fig 2.

**Construction of the evaluation index system of brownfield redevelopment**

Through analyzing the successful cases of brownfield redevelopment, such as BP Oil Company Ruins Park, Seattle Gas Plant Park, Toronto Danglesville park, Quarry Garden in Shanghai Botanical Garden, we concluded that the key factors for the success of brownfield redevelopment are the locations, sizes and pollution of brownfields themselves, the support of governments and society, the capital investment, and the environmental protection awareness of surrounding residents. Therefore, in this paper, we combined the Wuli, Shili and Renli dimensions to establish the evaluation indexes from six aspects, including brownfield pollution control, brownfield geographical conditions, policy support, capital investment, investment income and information orientation.

**Wuli dimension**

In the evaluation of brownfield redevelopment, Wuli refers to all material bases related to brownfields in brownfield redevelopment. From the perspective of brownfields themselves, the types of brownfields, pollution levels, area sizes, service conditions, geographic locations and treatment difficulties have a great impact on the brownfield government. The types of brownfields determine the difficulty of governance and the different ways of governance. According to the governance difficulty from easy to difficult, brownfields are divided into biological brownfields, chemical brownfields, physical brownfields, and radiation brownfields. From the service conditions of brownfields, more frequent use leads to more serious pollution, thus leading to greater treatment difficulty. Brownfields with less pollution can be treated preferentially to improve treatment efficiency. Brownfields with small contaminated areas are
easier to manage and require fewer resources. According to the locations of the brownfields, we can judge whether the brownfield governance is convenient and feasible. If brownfields are under utilization, contain many public buildings and are frequently used for daily activities, the governance difficulty may be greatly improved. In addition to the above factors, technology is also an important factor affecting the success of brownfield management. Making reasonable plans according to local conditions is also the key to the success of brownfield management. Therefore, clarifying the information of the Wuli dimension of brownfields is the basis of brownfield redevelopment and management.

Shili dimension
In the evaluation of brownfield redevelopment, Shili refers to the practical principles in brownfield redevelopment, including policy support, capital investment and investment income. From the successful cases of brownfield redevelopment in Britain, America and other countries, it can be seen that the governments’ attention and support are the key factors for the success of brownfield governance. The relevant legal provisions and the corresponding incentive policies issued by the governments can guarantee smooth brownfield governance. In China, although there are laws and regulations on environmental protection, there is still a lack of special laws and regulations on soil quality protection and pollution control. Therefore, only by combining the governance experience of other countries with China’s reality, issuing incentive policies, coordinating with relevant departments, and truly implementing brownfield governance, can brownfield governance be ensured.

Funds also play a decisive role in brownfield management. Funds are usually divided into government capital investment and outside investment according to the financing sources. Firstly, we should formulate the corresponding capital supervision policies to ensure the real implementation of funds. Secondly, outside investment often has many uncertain factors. Long project operation cycles, low technical contents and insufficient excavation of potential values of brownfields directly affect the credibility and investment attraction ability of projects. Sufficient attention, a sound legal system and a thorough management system are the key to attracting outside investment. In addition, the funds cannot be effectively applied in projects in the operation process, and the “secondary abandonment” caused by the wrong estimation of costs and benefits often leads to the investment of funds not meeting the governance of brownfield or excessive investment, resulting in the waste of funds. Therefore, the capital investment must be matched with brownfield governance in order to ensure effective governance.

Renli dimension
In the evaluation of brownfield redevelopment, Renli refers to all relevant information of brownfield learned through decision-making management, organization and coordination in brownfield redevelopment, including brownfield theory cognition, brownfield harm cognition, brownfield information control, and brownfield public opinion guidance. Brownfields are a relatively new concept in China and are not known by most people. The understanding of brownfields influences the difficulty of brownfield governance and investors’ investment in brownfield redevelopment. Moreover, brownfields themselves have some characteristics. They enjoy superior geographical locations and contain or possibly contain hazardous substances. Additionally, they are difficult to redevelop or reuse. No matter from the perspective of environmental protection or development, people should be aware of the development potential of the brownfields and their harm to society. Firstly, we must understand brownfield redevelopment projects in detail and establish a mature information management system to avoid
detours in the governance process. Secondly, we should actively guide public opinions on brownfield environmental protection. For the public, the information they receive directly affects their subjective views and judgments. Finally, the correct guidance of groups with certain public influence, such as authoritative institutions and certification institutions, may actively promote social support and participation.

Based on the analysis of brownfield redevelopment from the Wuli, Shili and Renli dimensions, we constructed the evaluation index system of brownfield redevelopment based on the WSR system methodology, as shown in Fig 3.

Catastrophe theory

The founder of the catastrophe theory is Rene Thom, a French mathematician. In his book *structural stability and morphogenesis* published in 1972, he pointed out that in the process of the system from a stable state to an unstable state, with the change of parameters, the unstable state would enter another stable state, and the system state would change in a moment [31–33]. The catastrophe progression method is a comprehensive evaluation method developed on the basis of the elementary catastrophe theory. It combines the catastrophe theory and fuzzy mathematics to produce a catastrophe membership function, performs comprehensive quantitative operation by normalization equations, and finally reduces comprehensive quantitative operation to a parameter, that is, calculates the total membership function to complete the evaluation of the research object [34].

Classification of catastrophe models

Catastrophe models are determined based on the evaluation index system. The types of commonly used catastrophe models include folding type, cusp type, dovetail type and butterfly type [35, 36]. The numbers of state variables and control variables of each model and the potential functions are shown in Table 2.

Dimensionless treatment of indexes

When the value range of each index in the evaluation system is different, the index needs to be dimensionless [37, 38]. Positive indexes mean that a larger index value is better. The
The dimensionless equation is:

$$y_{ij} = \frac{x_{ij} - x_{\text{min}(j)}}{x_{\text{max}(j)} - x_{\text{min}(j)}}$$  \hspace{1cm} (1)$$

Inverse indexes mean that a smaller index value is better. The dimensionless equation is:

$$y_{ij} = \frac{x_{\text{max}(j)} - x_{ij}}{x_{\text{max}(j)} - x_{\text{min}(j)}}$$  \hspace{1cm} (2)$$

where $y_{ij}$ is the dimensionless index value, $x_{ij}$ is the original index value, $x_{\text{min}(j)}$ is the minimum value in the index scoring line, and $x_{\text{max}(j)}$ is the maximum value in the index scoring line. When the index score value is within $[0, 1]$, the indexes need no dimensionless treatment.

**Normalization of catastrophe model**

Taking the cusp catastrophe model as an example, according to the catastrophe theory, when the system is in equilibrium, $f'(x) = 0$, that is, the equilibrium surface equation is $f(x) = x^3 + ax + b = 0$. The singular point set equation is obtained by calculating the second derivative of the potential function, that is, $f''(x) = 12x^2 + 2ax = 0$. The equilibrium surface equation and the singular point set equation are simultaneously calculated, and the scalar $x$ is eliminated to obtain $a = -6x^2$, $b = 8x^3$. Due to the nature of the fuzzy membership function, the value range of the control variable and the state variable must be within $[0, 1]$. Therefore, the equation of the cusp catastrophe model is $x_a = \sqrt{a}$, $x_b = \sqrt{b}$ [39, 40]. The normalization of other catastrophe models is described above, and the results are shown in Table 3.

**Calculation of the catastrophe progression value**

For the catastrophe model after normalization, the catastrophe progression value is calculated according to “complementary” or “non-complementary” principles [41, 42]. The principle of “complementarity” means that if control variables in the same system can complement each other, the average value of their function values is taken as the value of the state variable $x$; the “non-complementary” principle means that if the control variables in the same system

**Table 2. Elementary catastrophe model.**

| Catastrophe type | Number of state variables | Number of control variables | Potential function |
|------------------|---------------------------|-----------------------------|-------------------|
| Folding type     | 1                         | 1                           | $f(x) = x^3 + ax$ |
| Cusp type        | 1                         | 2                           | $f(x) = x^3 + ax^2 + bx$ |
| Dovetail type    | 1                         | 3                           | $f(x) = x^3 + ax^2 + bx^2 + cx$ |
| Butterfly type   | 1                         | 4                           | $f(x) = x^6 + ax^5 + bx^4 + cx^3 + dx$ |

**Table 3. Normalization equation of catastrophe series model.**

| Catastrophe type | Normalization equation |
|------------------|------------------------|
| Folding type     | $x_a = \sqrt{a}$      |
| Cusp type        | $x_a = \sqrt{a}$, $x_b = \sqrt{b}$ |
| Dovetail type    | $x_a = \sqrt{a}$, $x_b = \sqrt{b}$, $x_c = \sqrt{|c|}$ |
| Butterfly type   | $x_a = \sqrt{a}$, $x_b = \sqrt{b}$, $x_c = \sqrt{|c|}$, $x_d = \sqrt{|d|}$ |

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cannot complement each other, the minimum value is taken as the value of the state variable $x$.
In order to overcome the large numerical value of the catastrophe series method, the correction relationship between the initial score value $x_i$ and the comprehensive evaluation value $y_i$ is shown in Table 4 [43].

| Table 4. Correspondence between $x_i$ and $y_i$. |
|-----------------------------------------------|
|      | 0.1000 | 0.2000 | 0.3000 | 0.4000 | 0.5000 | 0.5500 | 0.6000 |
|-----------------|--------|--------|--------|--------|--------|--------|--------|
| Complementary  | 2      | 0.4642 | 0.5848 | 0.6694 | 0.7368 | 0.7937 | 0.8193 | 0.8434 |
|                 | 3      | 0.5623 | 0.6687 | 0.7401 | 0.7953 | 0.8409 | 0.8612 | 0.8801 |
|                 | 4      | 0.6310 | 0.7248 | 0.7860 | 0.8326 | 0.8706 | 0.8873 | 0.9029 |
| Non-complementary| 0.3162 | 0.4472 | 0.5477 | 0.6325 | 0.7071 | 0.7416 | 0.7746 |
| Complementary  | 0.7000 | 0.7500 | 0.8000 | 0.8500 | 0.9000 | 0.9500 | 1.0000 |
|                 | 2      | 0.8879 | 0.9086 | 0.9283 | 0.9473 | 0.9655 | 0.9830 | 1.0000 |
|                 | 3      | 0.9147 | 0.9306 | 0.9457 | 0.9602 | 0.9740 | 0.9873 | 1.0000 |
|                 | 4      | 0.9311 | 0.9441 | 0.9564 | 0.9680 | 0.9791 | 0.9898 | 1.0000 |
| Non-complementary| 0.8367 | 0.8660 | 0.8944 | 0.9220 | 0.9487 | 0.9747 | 1.0000 |

Calculation of the evaluation index weights of brownfield redevelopment

According to the requirements of the catastrophe progression method for the evaluation index system, the indexes in the evaluation index system must be subdivided from upper indexes to lower indexes in the form of a decomposition structure. In addition, the number of the lower indexes corresponding to the upper index should not exceed four. Moreover, the indexes at the same attribute level are sorted according to the important levels. Finally, only the original values of the underlying indexes need to be obtained. In this paper, we used the AHP method to calculate the index weights.

In this article, we used the WSR system methodology to analyze the influencing factors of brownfield redevelopment from the three aspects of Wuli, Shili and Renli and followed the principle of establishing regional, predictable, quantifiable and hierarchical indexes [13] to establish an evaluation index system composed of 1 target layer, 3 primary indexes, 6 secondary indexes and 19 third-class indexes. In order to facilitate the use of the indexes, each index is simply marked, as shown in Table 5.

Calculation process of the index weights

Experts from government departments, environmental protection departments, design units and construction units, university teachers and other stakeholders of brownfield redevelopment were invited to evaluate the importance of the indexes. The pairwise comparison judgment matrixes were listed according to the opinions of most experts, the weight of each index was calculated, and the consistency of the judgment matrixes was tested.

1) Calculation of the primary index weights

According to the expert evaluation, the pairwise comparison matrix of the primary indexes, Wuli ($A_1$), Shili ($A_2$) and Renli ($A_3$), is shown in Table 6.

Through calculation, the weights of $A_1$, $A_2$, and $A_3$ are 0.1220, 0.6483, and 0.2297, respectively. CI = 0.0018, and CR = 0.0032 < 0.1. The consistency test is passed, with satisfactory consistency.

2) Calculation of the secondary index weights
According to the expert evaluation, the pairwise comparison matrix of the Shili indexes policy support (A21), capital investment (A22) and investment income (A23) is shown in Table 7. Through calculation, the weights of A21, A22, and A23 are 0.0719, 0.2790, and 0.6491, respectively. CI = 0.0324, and CR = 0.0559 < 0.1. The consistency test is passed, with satisfactory consistency.

3) Calculation of the third-class index weights

1) Calculation of the weights of the brownfield pollution control indexes

According to the expert evaluation, the pairwise comparison matrix of the brownfield pollution control indexes brownfield pollution category (A111), brownfield pollution degree (A112), and limitations of brownfield governance technology (A113) is shown in Table 8.
Through calculation, the weights of $A_{111}$, $A_{112}$ and $A_{113}$ are 0.3196, 0.1220 and 0.5584, respectively. CI = 0.0091, and CR = 0.0176 < 0.1. The consistency test is passed, with satisfactory consistency.

2) Calculation of the weights of the brownfield geographical condition indexes

According to the expert evaluation, the pairwise comparison matrix of the brownfield geographical condition indexes brownfield use status ($A_{121}$), brownfield location ($A_{122}$), and brownfield area ($A_{123}$) is shown in Table 9.

Through calculation, the weights of $A_{121}$, $A_{122}$ and $A_{123}$ are 0.1571, 0.5936 and 0.2493, respectively. CI = 0.0268, and CR = 0.0515 < 0.1. The consistency test is passed, with satisfactory consistency.

3) Calculation of the weights of the policy support indexes

According to the expert evaluation, the pairwise comparison matrix of the policy support indexes regional planning ($A_{211}$), relevant policies ($A_{212}$), management system ($A_{213}$) and regulatory situation ($A_{214}$) is shown in Table 10.

Through calculation, the weights of $A_{211}$, $A_{212}$, $A_{213}$ and $A_{214}$ are 0.0589, 0.1470, 0.2793 and 0.5148, respectively. CI = 0.0094, and CR = 0.0105 < 0.1. The consistency test is passed, with satisfactory consistency.

4) Calculation of the weights of the capital investment indexes

According to the expert evaluation, the pairwise comparison matrix of the capital investment indexes construction costs ($A_{221}$), financing ability ($A_{222}$), governance costs ($A_{223}$) and fund matching degree ($A_{224}$) is shown in Table 11.

Through calculation, the weights of $A_{221}$, $A_{222}$, $A_{223}$ and $A_{224}$ are 0.2245, 0.0638, 0.1556 and 0.5561, respectively. CI = 0.0477, and CR = 0.0536 < 0.1. The consistency test is passed, with satisfactory consistency.

5) Calculation of the weights of the information orientation indexes

According to the expert evaluation, the pairwise comparison matrix of the information orientation indexes brownfield theory cognition ($A_{311}$), brownfield harm cognition ($A_{312}$), brownfield information control ($A_{313}$) and brownfield public opinion guidance ($A_{314}$) is shown in Table 12.

Through calculation, the weights of $A_{311}$, $A_{312}$, $A_{313}$ and $A_{314}$ are 0.0781, 0.2600, 0.1859 and 0.4760, respectively. CI = 0.0803, and CR = 0.0892 < 0.1. The consistency test is passed, with satisfactory consistency.
Ranking of the evaluation indexes and determination of scoring grades. Based on the above calculation results and relevant literature, each index is divided into four grades: [0.9, 0.1] (excellent), [0.8, 0.9) (good), [0.6, 0.8) (medium), and [0, 0.6) (poor). The evaluation index system and scoring standard of brownfield redevelopment are shown in Table 13.

Case analysis
According to the main data of China’s Third National Land Survey, as of December 31, 2019, China had 127,861,900 hm$^2$ of arable land, 20,171,600 hm$^2$ of garden land, 284,125,900 hm$^2$ of forest land, 264,530,100 hm$^2$ of grassland, 23,469,300 hm$^2$ of wetland, 35,306,400 hm$^2$ of urban, village and industrial and mining land, 9,553,100 hm$^2$ of transportation land, 36,287,900 hm$^2$ of land for water and water conservancy facilities. The data comparison between the second and third surveys on the current status of land use in China [44] is shown in Fig 4.

According to China’s Third National Land Survey, the total amount of construction land is 40,866,700 hm$^2$, an increase of 8,533,300 hm$^2$ or 26.5% over China’s Second National Land Survey. The GDP grew by 109.4%, and the urbanization rate of the resident population increased from 48.34% to 62.71% during this period. The increase in construction land generally coincides with the demand for land for economic and social development. However, China’s Third National Land Survey showed that the total scale of urban construction land was 10,333,300 hm$^2$, indicating insufficient conservation and intensification, with a large amount of inefficient and unused land in some places and a growing trend of brownfields.

Since 2016, China has begun implementing a contaminated land list system to control the redevelopment of contaminated land. The Problems and Countermeasures in the Development

| Table 10. Pairwise comparison matrix of the policy support indexes. |
|-------------------|-------------------|-------------------|-------------------|-------------------|
|                   | $A_{211}$         | $A_{212}$         | $A_{213}$         | $A_{214}$         |
| $A_{211}$         | 1                 | $1/3$             | $1/5$             | $1/7$             |
| $A_{212}$         | 3                 | 1                 | $1/2$             | $1/4$             |
| $A_{213}$         | 5                 | 2                 | 1                 | $1/2$             |
| $A_{214}$         | 7                 | 4                 | 2                 | 1                 |

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| Table 11. Pairwise comparison matrix of the capital investment indexes. |
|-------------------|-------------------|-------------------|-------------------|-------------------|
|                   | $A_{221}$         | $A_{222}$         | $A_{223}$         | $A_{224}$         |
| $A_{221}$         | 1                 | 4                 | 2                 | $1/4$             |
| $A_{222}$         | $1/4$             | 1                 | $1/3$             | $1/6$             |
| $A_{223}$         | 1/2               | 3                 | 1                 | $1/3$             |
| $A_{224}$         | 4                 | 6                 | 3                 | 1                 |

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| Table 12. Pairwise comparison matrix of the information orientation indexes. |
|-------------------|-------------------|-------------------|-------------------|-------------------|
|                   | $A_{311}$         | $A_{312}$         | $A_{313}$         | $A_{314}$         |
| $A_{311}$         | 1                 | $1/4$             | $1/2$             | $1/5$             |
| $A_{312}$         | 4                 | 1                 | 2                 | $1/3$             |
| $A_{313}$         | 3                 | 1/2               | 1                 | $1/2$             |
| $A_{314}$         | 5                 | 3                 | 2                 | 1                 |

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and Utilization of Contaminated Land in China’s Cities shows that as of October 2018, 27 of China’s 31 provincial capitals have published risk control lists of contaminated land in their regions (Fig 5). According to the compilation, there are 174 contaminated plots published. Tianjin, Chongqing and Shanghai have announced the most contaminated plots, with 21, 17 and 14 plots, respectively. Due to the limited availability of land resources, many local governments have chosen to develop contaminated land with high commercial value [45].

![Fig 4. China’s second and third national land surveys (unit: million hectares).](https://doi.org/10.1371/journal.pone.0277324.g004)
Recently, the number of contaminated plots in Chengdu has continued to rise. According to the List of the Risk Control and Remediation of Soil Contamination of Construction Land in Sichuan Province, as of July 2022, Sichuan Province has 70 contaminated plots, and the number of contaminated plots in Chengdu has changed from 5 to 17 [46]. The distribution of contaminated plots in Chengdu is shown in Fig 6.

**Project overview**

(1) Contrasting case—the renovation project of Shanghai Xintiandi in 1999–2001 [47]
The earliest Xintiandi Square (Fig 7) is located in the Taipingqiao area, south of Huaihai Middle Road in the central district of Shanghai. It is bordered by Huangpi South Road to the east, Zizhong Road to the south, Madang Road to the west and Taicang Road to the north.

The Taipingqiao area was designated as an old city renovation area in the 1990s due to a lack of infrastructure, the disrepair of typical Shanghai Shikumen buildings, poor living environments, crowded space, and congested and isolated traffic, which made it difficult to meet the requirements of the commercial development of the central area in Shanghai at that time. The challenge was to maximize the preservation of the historical relics and culturally
distinctive buildings, avoid submersion by or incompatibility with the environment after renovation, but realize the value of new commercial operations.

Based on the old Shikumen area, a landmark of modern architecture, Shanghai Xintiandi has firstly changed the original residential function of Shikumen buildings and endowed them with an innovative commercial business function, transforming these old buildings reflecting Shanghai’s history and culture into a fashionable, leisure and cultural entertainment center with an international level of dining, shopping and performing arts. In 2016, it was named by Forbes magazine as one of the top 20 civilization landmarks in the world.

(2) Study case—the renovation project of Wenjia Street in Qingyang District, Chengdu City in 2022.

Wenjia Street (Fig 8) is bordered by the Supo Branch Canal and Qingyang Mould Industrial Park to the east, Yanjing Phase III Subdivision to the north, and vacant land to the west and south.

The renovation project of an area in the west of Chengdu, China, is located at the junction of the old city and the new city, with rich surrounding supporting facilities, mature medical...
facilities, convenient transportation, developed commerce and educational resources. It belongs to the core area of the city. The area rose in size in the 1990s. Most houses are residents' resettlement houses, and some are small factories and workshops. Most people here are local residents. The area is characterized by dense buildings, narrow roads, small open space, dense personnel, and many pedestrians and vehicles. In recent years, with the rapid development of urban economy, the disadvantages of low-end operation, damaged and old houses, traffic congestion, ground damage, dirty and messy environment, fire hazards and chaotic rainwater drainage pipelines have gradually emerged in this area. This environment has seriously affected the image and quality of Chengdu, China. In the context of rational use of urban space and development and utilization of brownfields, the authorities have decided to renovate and upgrade this area since 2022.

Similar to the Shanghai Xintiandi project, Wenjia Street is an old neighbourhood in Chengdu, with disadvantages such as a lack of infrastructure and a poor living environment, but also features an excellent location and great development potential.

**Expert scoring**

In order to evaluate the feasibility of the brownfield renovation project, various factors were evaluated according to the established evaluation index system. Six experts from the government, environmental division, construction unit, development unit, university and consulting unit were invited to score the project according to its basic characteristics. The scoring standard is based on Table 13. The final scoring result is shown in Table 14.

**Calculation of the value of the catastrophe membership function**

In this paper, the index value is within [0, 1], so dimensionless treatment is not required. According to the catastrophe model shown in Table 2, the normalization equation shown in

| Primary index | Secondary index | Third-class index | Score | Mean value |
|---------------|-----------------|------------------|-------|------------|
| B₁            | B₁₁             | B₁₁₁             | 0.75  | 0.76 0.87 0.88 0.84 0.76 0.81 |
| B₁₂           |                 | B₁₂₁             | 0.82  | 0.60 0.78 0.74 0.60 0.83 0.73 |
| B₁₂           |                 | B₁₂₂             | 0.80  | 0.80 0.77 0.62 0.60 0.80 0.73 |
| B₁₂           |                 | B₁₂₃             | 0.70  | 0.80 0.80 0.80 0.82 0.80 0.79 |
| B₁₂           |                 | B₁₂₄             | 0.80  | 0.70 0.90 0.71 0.72 0.75 0.76 |
| B₁₃           |                 | B₁₃₁             | 0.50  | 0.64 0.46 0.36 0.49 0.57 0.50 |
| B₁₃           |                 | B₁₃₂             | 0.60  | 0.52 0.50 0.30 0.68 0.58 0.53 |
| B₁₃           |                 | B₁₃₃             | 0.60  | 0.44 0.48 0.60 0.66 0.54 0.55 |
| B₁₃           |                 | B₁₃₄             | 0.92  | 0.72 0.90 0.78 0.70 0.71 0.79 |
| B₂            |                 | B₂₁₁             | 0.63  | 0.71 0.63 0.59 0.76 0.76 0.68 |
| B₂            |                 | B₂₁₂             | 0.50  | 0.36 0.40 0.28 0.37 0.54 0.41 |
| B₂            |                 | B₂₁₃             | 0.60  | 0.60 0.72 0.58 0.65 0.62 0.63 |
| B₂            |                 | B₂₁₄             | 0.50  | 0.23 0.41 0.27 0.26 0.27 0.32 |
| B₃            |                 | B₃₁₁             | 0.92  | 0.94 0.98 0.95 0.99 1.00 0.96 |
| B₃            |                 | B₃₁₂             | 0.83  | 0.79 0.90 0.89 0.71 0.72 0.81 |
| B₃            |                 | B₃₁₃             | 0.84  | 0.85 0.85 0.73 0.77 0.74 0.80 |
| B₃            |                 | B₃₂₁             | 0.80  | 0.85 0.84 0.83 0.81 0.66 0.80 |
| B₃            |                 | B₃₂₂             | 0.70  | 0.69 0.60 0.62 0.72 0.63 0.66 |
| B₃            |                 | B₃₂₃             | 0.82  | 0.80 0.87 0.77 0.90 0.79 0.83 |

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Tables 2, 3 and the “complementary” and “non-complementary” principles, the catastrophe membership function values of the secondary indexes, primary indexes and target layer were obtained.

(1) Calculation of the secondary indexes

Capital investment \( B_{12} \) consists of four indexes and is of the butterfly type. The indexes complement each other, then:

\[
B_{12} = \left( \sqrt{B_{121}} + \sqrt{B_{122}} + \sqrt{B_{123}} + \sqrt{B_{124}} \right) / 4 = 0.9110
\]

Policy support \( B_{13} \) is composed of four indexes and is of the butterfly type. There is complementarity among the indexes, then:

\[
B_{13} = \left( \sqrt{B_{131}} + \sqrt{B_{132}} + \sqrt{B_{133}} + \sqrt{B_{134}} \right) / 4 = 0.8329
\]

Information orientation \( B_{21} \) consists of four indexes and is of the butterfly type. The indexes complement each other, then:

\[
B_{21} = \left( \sqrt{B_{211}} + \sqrt{B_{212}} + \sqrt{B_{213}} + \sqrt{B_{214}} \right) / 4 = 0.8137
\]

Brownfield geographical condition \( B_{31} \) is composed of three indexes and is of the dovetail type. There is no complementarity among the indexes, then:

\[
B_{31} = \min(\sqrt{B_{311}}, \sqrt{B_{312}}, \sqrt{B_{313}}) = 0.8944
\]

Brownfield pollution control \( B_{32} \) consists of three indexes and is of the dovetail type. The indexes do not complement each other, then:

\[
B_{32} = \min(\sqrt{B_{321}}, \sqrt{B_{322}}, \sqrt{B_{323}}) = 0.8124
\]

(2) Calculation of the primary indexes

Shili \( B_1 \) is composed of three indexes and is of the dovetail type. There is complementarity among the indexes, then:

\[
B_1 = \left( \sqrt{B_{11}} + \sqrt{B_{12}} + \sqrt{B_{13}} \right) / 3 = 0.9416
\]

Wuli \( B_3 \) consists of two indexes and is of the cusp type. The indexes complement each other, then:

\[
B_3 = \min(\sqrt{B_{31}}, \sqrt{B_{32}}) = 0.9013
\]

(3) Calculation of the comprehensive evaluation index

Comprehensive evaluation index \( B \) is composed of three indexes and is of the dovetail type. The indexes complement each other, then:

\[
B = \left( \sqrt{B_1} + \sqrt{B_2} + \sqrt{B_3} \right) / 3 = 0.9594
\]

Comparing the results of the comprehensive evaluation index, primary indexes and secondary indexes with Table 4, we obtained the final evaluation results of the feasibility of the brownfield renovation project, as shown in Table 15.
Results and discussion

According to the evaluation results in Table 15, the redevelopment feasibility grade of the brownfield is good, indicating that the brownfield is suitable for redevelopment. It can be seen from the index scores of each level that the Renli evaluation level is good in the three aspects, indicating that the concept of environmental protection has been strengthened, the requirements for the living environment are getting higher, and the desire for community transformation is stronger. It can be seen from the scores of each secondary index that among the six aspects of brownfield pollution control, brownfield geographical conditions, policy support, capital investment, investment income and information orientation, the evaluation score of the investment income is the highest, and the investment income brought by the redevelopment of the project is the most obvious. In the capital investment, the matching degree of investment and brownfield governance and the implementation of relevant measures of local government investment are also obvious advantages. The second is the brownfield geographical conditions, and the third is the brownfield pollution control, showing that the location advantage of the brownfield is significant, the pollution of the brownfield can be well dealt with, and the overall conditions of the brownfield are superior. Generally speaking, there is still a lack of policy support. Although attention is paid to the overall regional planning, the management system, supervision and implementation ability and supporting policies for the brownfield renovation project need to be strengthened. From the perspective of information orientation, the overall score of the brownfield renovation project is not high, indicating that the public’s understanding of brownfield knowledge and the harm of brownfield pollution need to be improved.

Conclusions and future research orientations

In this paper, we regarded the brownfield redevelopment evaluation index system as an interrelated organic whole and constructed the brownfield redevelopment evaluation model by combining the WSR system methodology with the catastrophe progression method. The feasibility of the brownfield redevelopment evaluation system established in this paper was verified by an actual case. In the process of brownfield redevelopment research, the following conclusions were drawn:

1. The WSR system methodology was applied to the feasibility evaluation of brownfield redevelopment, and the problem of brownfield redevelopment was analyzed from the three dimensions of Wuli, Shili and Renli. Not only the conditions and characteristics of the brownfield were considered, but also the policies, regulations and relevant information

Table 15. Evaluation results of the feasibility of the brownfield redevelopment project.

| Comprehensive evaluation index |      |      | Grade |
|--------------------------------|------|------|-------|
|                                | B    | y    | x     |
| Primary index                  |      |      |       |
| B                              | 0.9594 | 0.8472 | II    |
| B1                             | 0.9416 | 0.7861 | III   |
| B2                             | 0.8137 | 0.8137 | II    |
| B3                             | 0.9013 | 0.7322 | III   |
| Secondary index                |      |      |       |
| B11                            | 0.8100 | 0.8100 | II    |
| B12                            | 0.9110 | 0.6275 | III   |
| B13                            | 0.8329 | 0.4008 | IV    |
| B21                            | 0.8137 | 0.3567 | IV    |
| B31                            | 0.8944 | 0.8000 | II    |
| B32                            | 0.8124 | 0.6600 | III   |

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affecting the decision-making of brownfield redevelopment were considered. Moreover, the coordination of the three dimensions enhanced the reliability of the evaluation index system of brownfield redevelopment.

2. The catastrophe progression method was applied to the feasibility evaluation of brownfield redevelopment. Considering the interaction among the indexes, we calculated the index values of the upper indexes layer by layer through the score values of the lower indexes, obtained the importance ranking of the indexes, effectively reducing the subjective error caused by the calculation of index weights, and had a more objective evaluation of all aspects of brownfield redevelopment. The developers can comprehensively consider the response measures of various influencing factors in the whole process of brownfield redevelopment.

3. Brownfield redevelopment involves many stakeholders, and the conditions of brownfields and the surrounding environments are complex. Therefore, future studies on brownfields and the surrounding environments should focus on how to reasonably divide the rights and responsibilities of stakeholders and scientifically formulate policies and legal measures to effectively solve their conflict of interests; in addition, during development evaluation, establishing a more detailed and data-based evaluation index system and forming an information system will be the key to the next research on brownfield redevelopment.

Author Contributions

Formal analysis: Pan Haize.
Investigation: Liu Chuan.
Methodology: Li Xiaoqin.
Project administration: Wei Yan.
Resources: Jiang Haidan.
Software: Zhang Changliang.
Writing – original draft: He Jian.
Writing – review & editing: Hu Hao.

References

1. Liedekerke Van et al. Progress in the Management of Contaminated Sites in Europe. 2014. https://doi.org/10.2788/4658
2. Green T.L. Evaluating predictors for brownfield redevelopment[J]. Land Use Policy, 2018, 73:299–319.
3. CPRE.Recycling Our Land: The State of Brownfield 2020—An Updated Analysis of the Potential of Brownfield Land for New Homes [EB/OL]. https://www.cpre.org.uk/wp-content/uploads/2020/10/Recycling-our-land-the-state-of-brownfield-report-Oct-2020.pdf.
4. Fei Lv, Tingting Yu. Study on urban brownfield transformation in China based on Landscape Urbanism: Taking the landscape transformation of prosperous block section of Majiagou in Harbin as an example [J]. Chinese garden, 2014 (3): 68–73.
5. Tomáš Krejčí et al. Spatial Unevenness of Formation, Remediation and Persistence of Post-Agricultural Brownfields[J]. Land, 2021, 10(3): 325.
6. Martinat Stanislav. et al. Re-use of regenerated brownfields: Lessons from an Eastern European post-industrial city[J]. Journal of Cleaner Production, 2018, 188:536–545.
7. Pytel Sławomir. et al. Transformation Directions of Brownfields: The Case of the Górniośląsko-Zagłębiowska Metropolis. Sustainability, 2021, 13(4): 2075.
8. Bieback Karin. Housing Development on Brownfield Sites [J]. Environmental Law Review, 2002.
9. Tiesdell Steven, Adams David. Design matters: major house builders and the design challenge of brownfield development contexts [J]. Journal of Urban Design, 2004.
10. Kang Cao, Tao Jin. Land use strategy of “brownfield redevelopment” abroad and Its Enlightenment to China [J]. China population, resources and environment, 2007 (06): 124–129.
11. Kang Cao, he Huachun. Uncover the secrets of “brownfield” [J]. China land, 2007 (08): 43–44.
12. Yuhu Luo. Current situation and Countermeasures of urban brownfield management in China [J]. Henan science and technology, 2020(10):142–144.
13. Peng Guo, Yanhua Liang, Yuming Zhu. Multi level grey evaluation of brownfield redevelopment based on combination weight method [J]. Operations research and management, 2010, 19 (05): 129–134.
14. Yan Fang. Study on suitability evaluation of brownfield redevelopment [D]. Nanjing Agricultural University, 2009.
15. Zihao Wang et al. Spatial Identification and Redevelopment Evaluation of Brownfields in the Perspective of Urban Complex Ecosystems: A Case of Wuhu City, China [J]. International Journal of Environmental Research and Public Health, 2022, 19(1):478.
16. Ye Chen et al. A strategic classification support system for brownfield Redevelopment [J]. Environ. Model. Softw. 2009, 24(5):647–654.
17. Le Sage Pascal; Deschenes Louise; Samson Rejean. Evaluating holistic environmental consequences of brownfield management options using consequential life cycle assessment for different perspectives [J]. Environmental management. 2007, 40(2):323–37.
18. Deyi Hou et al. Factor analysis and structural equation modelling of sustainable behaviour in contaminated land remediation[J]. J. Clean. Prod. 2014, 84:439–449.
19. Lin Xiangyi; Zhang Qingpu; Han Xiao ain. Application of Wuli-Shili-Renli system methodology in knowledge management[J]. Kybernetes, 2009, 38 (3/4):346–353.
20. Hongyan Zhang, song Yinqiu Wang Deqing, pan Shengjie. Study on the construction of environmental pollution control evaluation system in coastal areas based on WSR methodology [J / OL]. Management review: 1–11 [2021-08-17].
21. Abdelbasset W.K., Nambi G., El-Sakhawy M.A.-M., Mahmoud M.Z., Alrawi B.S., Elsayed S.H. (2022). Study on WSR-based community healthy food distribution design method. Food Science and Technology (Brazil), 42, art. no. e70521. https://doi.org/10.1590/fst.70521
22. Zhou Q., Bao Y., Zhao Y., He X., Cui C., & Liu Y. (2022). Impacts of Government Credit on Government Performance of Public-Private-Partnership Project in China: A WSR System Theory Perspective. Sustainability, 14(11), 6886. https://doi.org/10.3390/su14116886
23. Li G., Zhou Y., Liu F., & Wang T. (2021). Regional differences of manufacturing green development efficiency considering undesirable outputs in the yangtze river economic belt based on super-SBM and WSR system methodology. Frontiers in Environmental Science, 8, 631911. https://doi.org/10.3389/fenvs.2020.631911
24. Yu X., Ma S., Cheng K., & Kyriakopoulos G. L. (2020). An evaluation system for sustainable urban space development based in green urbanism principles—A case study based on the Qin-Ba mountain area in China. Sustainability, 12(14), 5703. https://doi.org/10.3390/su12145703
25. Tsiantikoudis S., Zafeiriou E., Kyriakopoulos G., & Arbatzis G. (2019). Revising the environmental Kuznets Curve for deforestation: An empirical study for Bulgaria. Sustainability, 11(16), 4364. https://doi.org/10.3390/su11164364
26. Ji B., Liu Y., & Jin Z. (2018). An evaluation of the design and construction of energy management platform for public buildings based on WSR system approach. Kybernetes. https://doi.org/10.1108/K-07-2017-0265
27. Tao Chen, Jinxian Zhao, Kejie Jiang. Study on fuzzy evaluation of subway shield construction safety management based on WSR and C-OWA [J]. Journal of engineering management, 2019, 33 (05): 68–73.
28. Zijun Mao, Guoqie Zhao, Haifeng Wang, Mofei Zhao. Discovery and comparative study of three generation paths of WSR methodology [J]. Management review, 2021, 33 (05): 44–56.
29. Hejiang Wu. Research on labor education evaluation based on WSR system methodology [J]. Curricular teaching research, 2020 (09): 81–88.
30. Mohammad Ali Ghorbani et al. Study of discontinuities in hydrological data using catastrophe theory. Hydrological Sciences Journal, 2010, 55(7):1137–1151.
32. Kozak JJ; Benham CJ. Denaturation: an example of a catastrophe. Proc Natl Acad Sci USA, 1974, 71 (5):1977–81. https://doi.org/10.1073/pnas.71.5.1977 PMID: 4525309
33. Meimei Wu et al. Evaluation of the Benefits of Urban Water Resource Utilization Based on the Catastrophe and Emergy Methods[J]. Water Resources Management, 2020, 34: 1843–1853.
34. Li Baode; Li Jing; Lu Jing. Research on the Coupled Risk of Key Nodes in Maritime Transport Based on Improved Catastrophe Theory. Sustainability, 2019, 11(17): 4640.
35. Zhigang Yan, Lifeng Du, Xueli Wang. Study on Green Construction Evaluation Based on catastrophe progression method [J]. Construction technology, 2012, 41 (21): 25–29.
36. Thom R. Structural stability and morphogenesis[CP/DK]. Boca Raton: CRC Press, 2018.
37. Du song Xiao Ming, Juntao Chen. Study on catastrophe series evaluation method for risk analysis of cavern block [J/OL]. Geotechnical mechanics, 2021 (09): 1–11 [2021-08-17].
38. Laishram Kanta Singh; Madan K. Jha; Chowdary V. M. Application of catastrophe theory to spatial analysis of groundwater potential in a sub-humid tropical region: a hybrid approach[J]. Geocarto International, 2020.
39. Shigonglong Zhang Yi, Hongxia Li, Shuicheng Tian, Qian Wang. Research on safety investment evaluation of coal enterprises based on catastrophe progression method [J/OL]. Journal of safety and environment: 1–8 [2021-08-17].
40. Zaoshui Hou, Mingtao Jia, Jiao Chen. Ecological security assessment of Changsha Based on catastrophe progression method and principal component analysis [J]. Journal of safety and environment, 2015, 15 (02): 364–369.
41. Chaofeng Liu, Jingyu Su, Wei Wang, Jie Tian, Zhitao Wang. Catastrophe model for regional earthquake disaster carrying capacity evaluation [J]. Chinese Journal of safety Sciences, 2011, 21 (11): 8–15.
42. Minghui Wang, Qiao Zhang, Feifei Ling, Shaoquan Ni. Study on Construction Evaluation of Green high-speed railway based on catastrophe series method [J]. Journal of railway engineering, 2017, 34 (02): 76–80.
43. Zhenhua Luo, Mengfan Zhong, Nian Zhang, Ming Lou, pan Haize He Jian, et al. Study on comprehensive environmental impact assessment of shale gas exploration and production based on catastrophe progression method [J]. Geology and exploration, 2018, 54 (01): 174–182.
44. Ministry of Natural Resources of the People’s Republic of China. Available online: https://www.mnr.gov.cn/zt/td/dscqggtz/ (accessed on 24 September 2022).
45. GreenPeace; Lishui Institute of Ecological Environment, Nanjing University. Problems and Countermeasures in the Development and Utilization of Urban Polluted Land in China. Available online: https://www.greenpeace.org.cn/developing-the-polluted-land-under-chinas-cities-problems-and-solutions-report/ (accessed on 20 September 2022).
46. Department of Ecology and Environment of Sichuan Province. Available online:http://sthjt.sc.gov.cn/ sthjt/c103951/2022/7/14/4ed0d295233de4ca5a2d9bb11db2324.shtml (accessed on 15 September 2022).
47. Yaling Shi, Yong Huang. Spatial reshaping in the renewal of historical districts—the case of Xintiandi and Tianzifang districts in Shanghai[C]. 60 years of planning: achievements and challenges—Proceedings of the 2016 China Urban Planning Annual Conference (08 Urban Culture), 2016:308–317.