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A model approach for post evaluation of adaptive reuse of architectural heritage: a case study of Beijing central axis historical buildings

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Abstract

The adaptive reuse of architectural heritage is the basis of embodying its core value, bringing new life to heritage architecture, and is an important way to integrate it into contemporary development. In many current studies, the adaptive reuse of architectural heritage focuses on the research framework of adaptive reuse and the most effective method for adaptive reuse of a certain building. In the whole process, the post evaluation strategy of adaptive reuse based on specific cultural background is ignored, and the adaptive reuse of heritage buildings is a dynamic process. Therefore, this study takes 9 heritage sites along the central axis of Beijing (including three types of single buildings, architectural complexes, and historical and cultural district) as examples. The 25 factors affecting the adaptive reuse of architectural heritage are extracted by the literature retrieval method, and are divided into three categories according to the content: existing fabric, spatial character and policy and value. Then the analytic hierarchy process and fuzzy comprehensive evaluation are used to calculate the factors of 9 heritage sites in matrix, and finally obtain the reuse score of each heritage site. The results show that Meridian Gate has the highest comprehensive score for reuse in single buildings, the Forbidden City has the highest score for reuse in building complex, and Qianmen Street has the highest score in historical and cultural district. This study provides post-evaluation methods and strategies for the adaptive reuse of architectural heritage. Finally, a post-evaluation framework for the adaptive reuse of architectural heritage is formed. Finally, a post-evaluation framework for the reuse of architectural heritage against a specific cultural background has been formed. In the future, the status of the reuse of architectural heritage can be evaluated to maintain its proper authenticity, integrity and sustainability at any time. It can also guide the relevant decision-making before the adaptive reuse of architectural heritage and the optimization process after the adaptive reuse of architectural heritage.

Keywords Adaptive reuse, Central axis of Beijing, Architectural heritage, Fuzzy comprehensive evaluation, Post evaluation

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Introduction and research aims

Architectural heritage is the core of urban historical resources. It is also an important carrier of urban cultural value. The adaptive reuse of architectural heritage brings new life to buildings [1]. Heritage buildings retain their original appearance, historical mode, layout, architectural elements and historical relevance. At the same time, they make valuable contributions to the modern urban environment and meet the functional requirements related to the social environment [2]. And it transfer its value to the future. Therefore, the adaptive reuse of architectural heritage is the main embodiment of realizing the sustainability of urban culture [3].

As for the International Document and Charters on the adaptive reuse of architectural heritage, the Amsterdam paper issued in 1975 pointed out that the protection of heritage should not only focus on the cultural value of the building, but also on its use value. Only by considering these two values at the same time can we correctly explain the social issues of overall protection. The adaptive reuse of buildings endows buildings with functions that meet the needs of contemporary life. These functions can respect their characteristics and ensure their survival [4]. The Nara Document on Authenticity issued in 1994 mentioned the importance of heritage reuse [5], and the Faro Convention on the Value of Cultural Heritage for Society in 2005 mentioned that heritage should be fully reused according to the needs of the times [6]. In 2011, the Paris Declaration on Heritage as a Driver of Development proposed that the reuse of architectural heritage contributes to the development of cities and the sustainability of heritage [7]. The Burra Charter in 2013 proposed that new functions should maintain the vitality of historical buildings [8]. It can be seen that international documents gradually emphasize the integrity, sustainability and vitality of the adaptive reuse of architectural heritage.

In the research of adaptive reuse of architectural heritage, more research focuses on the decision-making process. This process is divided into 10 steps: 'initiative', 'analysis of heritage buildings', 'value assessment, 'mapping level of significance', 'definition of adaptive reuse potential', 'definition of design strategy', 'final decision-making', 'execution', 'maintenance', and 'evaluation after years' [9]. Damla Mısırlısoy and Kağan Günçe divided the decision-making process into five steps: 'definition of actions in decision making', 'analysis of existing fabric', 'decision of conservation actions', 'definition of adaptive reuse potentials', and 'decision of functional changes' [10]. Waleed Tarek Ali Shehata, Yasser Moustafa and Lobna Sherif divided the framework of adaptive reuse of architectural heritage into three steps: 'building preservation', 'Success of new use', and 'Local community development' [11]. It can be seen that these decision-making processes include the analysis of architectural heritage, the analysis of new uses and future development [12]. However, as a dynamic process, there is no separate study on the post use evaluation of architectural heritage.

At present, for the decision-making research on the adaptive reuse of historical buildings, the commonly used method is the qualitative research method of expert scoring, which is mainly aimed at scoring the factors that affect the adaptive reuse of historical buildings, and lists the problems related to decision-making [13]. The commonly used quantitative research methods are mostly analytic hierarchy process (AHP) and ranking method [14]. These two methods establish an evaluation system for the indicators that affect the adaptive reuse decision of historical buildings, calculate the weight of the indicators, compare them, rank the importance of the indicators, and find the most important decision indicators. As for the adaptive reuse of historical buildings, a one-time decision is not necessarily applicable to every building. Therefore, a more comprehensive method is needed to evaluate the state of the buildings after use to determine whether the adaptive reuse mode and current situation are applicable to the historical buildings.

At present, in the process of adaptive reuse of architectural heritage, there are problems that the new functions of architecture are not consistent with the historical background of architecture [15]. There is also the problem of neglect of architectural historical information in the process of adaptive reuse [16]. In addition, the problem of low comprehensive utilization rate of historical buildings also exists [17]. Therefore, it is necessary to evaluate the state of the reuse of architectural heritage. The purpose of this is to find out the problems in the reuse of architectural heritage, adjust the way of reuse of architectural heritage at any time, and make it fully sustainable for reuse. At the same time, in order to make a comprehensive and accurate assessment of the state of reuse, it is necessary to divide the architectural heritage into three categories according to the scale, one is the single building, the second is the building complexes, and the third is the historical and cultural district. The three types of architectural heritage have different characteristics. The single building has a single function. The building group is composed of buildings. Different combination methods are applicable to different functions, while the historical and cultural district contains more historical environment. In order to fill in the research gap, this paper uses a comprehensive evaluation method to evaluate the adaptive reuse of historical buildings. The current research defect is that there is no comprehensive study on the state of the architectural heritage after adaptive reuse according to the three types of historical buildings. In view of the inadequacy of the current research, this study divides the types of historical buildings are classified into single buildings, architectural complexes and historical and cultural district. Secondly, the comprehensive evaluation method is adopted, which is the combination of qualitative and quantitative methods. The qualitative method is experts' scoring of the current reuse status of architectural heritage, and the quantitative research method is the combination of analytic hierarchy process and fuzzy comprehensive evaluation.

The adaptive reuse of historical buildings is a dynamic process serving the contemporary era, so it is necessary to accurately evaluate the state of the reused buildings [18]. The purpose is to timely adjust the adaptive reuse strategy, optimize the reuse method, and make it play a greater role in serving the present. The post adaptive reuse evaluation is different from the pre adaptive reuse evaluation. Its difference is that it has people's use experience [19]. Therefore, a comprehensive quantitative method is more needed to analyze the relationship between various factors, rather than just analyzing the ranking of the importance of each factor. This study uses the fuzzy comprehensive evaluation method to achieve this goal.

The new contributions of this study are as follows: first, a research framework for post evaluation of adaptive reuse of historical buildings is proposed, and factors that need to be optimized and improved in the process of continuous adaptive reuse are found. Secondly, based on the three types of single buildings, building complex and historical and cultural district, this study comprehensively analyzes the evaluation of the adaptability and reuse of historical buildings. Thirdly, this study uses the analytic hierarchy process and fuzzy comprehensive evaluation method to comprehensively evaluate the adaptability of historical buildings after adaptive reuse. This study provides a framework and method for post evaluation of the adaptive reuse of historical buildings, which can be used to further optimize the adaptive reuse of historical buildings and accurately find relevant indicators for improvement.

Literature review

The literature review includes three aspects. The first part is the difference between pre-evaluation and post-evaluation of heritage buildings adaptive reuse. The second part is the research on the adaptive reuse of heritage buildings. The third part is the related research on the evaluation methods of the adaptive reuse of heritage buildings.

The evaluation of heritage buildings before and after adaptive reuse has both similarities and differences. There is not much difference between the two in the principles, methods and indicators of evaluation. The difference between the two evaluations is that the pre-evaluation is conducted before and during the implementation of the project [20], and the post-evaluation is conducted after the project is completed and used for a period of time [21]. Secondly, the functions of the two are not the same. The pre-evaluation is the starting point of the project. It mainly uses the predicted technology and data to evaluate the future status of the project. The post-evaluation is to summarize the use of the project after it has been used for a period of time. In addition, the depth of the two evaluations are different. The pre-evaluation is a pre-judgment for the future, while the post-evaluation is a summary of the pre-evaluation and a new judgment for the future [22]. For example, Ragheb G. A.'s evaluation of the building structure before adaptive reuse of the building heritage aims to make the judgment of the building adaptive reuse function and the improvement plan for the structure during the implementation of the reuse project [23]. And J Mundo Hern á ndez evaluated the building structure in the study of the post-evaluation of adaptive reuse of the building heritage, with the purpose of evaluating the current use status of the building structure and the defects of the current structure [24].

The research on the adaptive reuse of heritage buildings mainly focuses on nine points: physical condition function update part spatial form space quality related policy heritage value economic value and memorial value (Table 1). There are differences between the evaluation of these indicators before and after adaptive reuse of architectural heritage. The indicators used before adaptive reuse are to study the status of heritage buildings before adaptive reuse. The evaluation after adaptive reuse is to study the state of the architectural heritage after adaptive reuse, and of course it will also be compared with the state before adaptive reuse, and whether the intervention degree of the heritage buildings is reasonable.

Physical condition (B1) refers to the state of the heritage building itself [25] (Table 1). This state is an important basis for deciding how to adaptive reuse the building, including the location of the building, which is close to residential areas or schools. It also includes the facades, materials, structural methods and construction techniques of heritage buildings [26]. These are the main historical information of heritage buildings, as well as the material basis for adaptive reuse and transformation [27].

The research on function (B2) mainly includes three aspects: first, the continuation of the original function of heritage buildings; Second, the new functions of heritage buildings; the third is to add some new functions to the original functions of heritage buildings [28] (Table 1). The continuation of the original function refers to the renovation of the components and structures of the architectural heritage and the renewal of the surrounding

Table 1 Relevant research content and factors extraction

Relevant research study	Content description	Factors	Index	Target classification
Kincaid [42], Mason and Avrami [43], Brandenburg [44], Guy and McLendon [45], Engel [46] and Dan et al. [47]	The location of a building in a city or area	*u* 1 Location	B1 Physical condition	A1 Existing fabric
	Facade style and details	*u* 2 Facade features		
	Main materials of facade and structure	*u* 3 Material		
	Structural bearing mode	*u*4 Structure system		
	Special construction technology	*u*5 Construction techniques		
Bullen and Love [48], Cantacuzino [49], Smith [50] and Douglas [51]	All previous functions	*u*6 Original function	B2 Function	
	Functions being used now	*u* 7 New function		
	Sub functions have been added to the previous functions without completely changing the original functions	*u* 8 Adding some sub-function		
Merlino [52], Plevoets and Van Cleempoel [53], Pendlebury et al. [54]	The original material is not applicable to the current function, and the new material replaces the original material	*u* 9 New materials	B3 Update part	
	Application of new technology in historical buildings	*u*10 New techniques		
	New decoration for new functions	*u*11 New decoration		
Ching [55], Schittich [56] and Radwan [57]	Main function space	*u*12 Main space	B4 Spatial form	A2 Spatial character
	Space for traffic	*u*13 Traffic space		
	Connection and combination of spaces	*u*14 Spatial organization		
	Space outside the building	*u*15 Outdoor space		
	Size of space	*u*16 Spatial scale	B5 Space quality	
	Landscape elements in space	*u*17 Landscape factor		
Delafons and Delafons [58], Barker and Marano [59] and Pickard [60]	International general charters on reuse	*u*18 International charters	B6 Related policy	A3 Policy and value
	Local requirements for building reuse	*u*19 Local principles		
	Local laws on building reuse	*u*20 Local laws		
Ruskin [61] and Stubbs [62]	Cultural value and information of history	*u*21 Historical culture and value	B7 Heritage value	
Loulanski [63] and Throsby [64]	Expenditure on reuse	*u*22 Decoration cost	B8 Economic value	
	Source of income for reuse	*u*23 Reuse income		
Feilden [65] and Larkham [66]	Memory and intangible cultural heritage	*u*24 Memory information	B9 Memorial Value	
	Special customs	*u*25 Cultural content		

environment, without changing the characteristics of the heritage buildings, so that they can continue to maintain their original functions [29]. But it usually adds modern infrastructure. For example, some ancestral temples, temples and churches are mainly used for the situation where the functions of such buildings still meet the needs of the contemporary. However, modern equipment such as air conditioning and monitoring need to be added. The new function of the heritage buildings means to completely change the original function of the heritage buildings, but not change the characteristics of the architectural heritage [30]. This approach is mainly used when the function of the building has been completely replaced by the new content of contemporary development. The heritage building adds some new functions to the original functions, which means that it retains some of its original functions and adds some new functions [31]. It is usually the renewal and protection of historical blocks, which adds sightseeing and leisure functions on the basis of the original functions.

Update part (B3) refers to new materials, new technologies and new decoration that serve the adaptive reuse of heritage buildings without changing the characteristics of architectural heritage [32] (Table 1). New materials and new decoration are the replacement or repair of damaged raw materials. New technology refers to the installation of modern electronic products such as air conditioners and monitoring equipment in historical buildings, with the purpose of serving contemporary adaptive reuse [33].

Spatial form (B4) and space quality (B5) are the spatial characteristics of heritage buildings (Table 1). Space includes the main use space, circulation spaces, space combination mode and outdoor space of buildings [34]. The characteristics of these spaces determine the function of adaptive reuse. For example, open indoor space is suitable for exhibition halls and public activities. The quality of space is the scale of indoor and outdoor space and environmental factors, which also make it an important factor to evaluate the adaptive reuse of historical buildings [35].

Related policy (B6) refers to policies and laws related to the adaptive reuse of architectural heritage, including international regulations and local regulations and laws [36]. These policy documents also provide ideas and constraints for the adaptive reuse of heritage buildings [37]. The value mainly includes three aspects: heritage value, economic value and memory value. The heritage value (B7) is mainly the historical and cultural information of architecture. Economic value (B8) mainly refers to the cost and benefit of building adaptive reuse [38]. Memory value (B9) refers to cultural content and intangible cultural heritage information. These values should be fully considered in the adaptive reuse of architectural heritage (Table 1).

The evaluation methods on the adaptive reuse of architectural heritage can be divided into qualitative research method and quantitative research method [39]. In qualitative research methods, literature review and questionnaire survey are widely used. Through comprehensive analysis of literature and cases, the most effective way to adaptive reuse heritage buildings is obtained, or the questionnaire is obtained through literature analysis, and the results of the questionnaire are analyzed [40]. The quantitative analysis method, commonly used, is the analytic hierarchy process, which requires experts to score each factor first, and then get the weight of each factor, so as to know the importance of each factor for the adaptive reuse of architectural heritage [41].

Methodology

Overview of methodology

This study is divided into four steps. Through these four steps, a framework for post evaluation of architectural heritage adaptive reuse is formed in three types (Fig. 1).

Step 1. According to the literature search, 25 factors, 9 indicators and 3 target values related to the adaptive reuse of architectural heritage were determined (Table 1).

Step 2. Nine historical sites along the central axis of Beijing were selected according to different types, including single buildings, architectural complexes and historical and cultural districts. Single building is a historical building, and its adaptive reuse mode and function are single. The architectural complex is presented in the form of architectural combination, which is an orderly combination of buildings with rich outdoor space. Historic and cultural blocks are areas with rich heritage, concentrated historical buildings, complete and authentic traditional patterns and historical features, and a certain scale. These three types are different scales of historical buildings (Table 18).

Case selection criteria:

1. Architectural heritage that has been adaptive reused
2. Located on the central axis of Beijing. It is the core area of Beijing's urban historical spatial structure and dominates the urban function and spatial pattern. Beijing Central Axis is applying for world cultural heritage.
3. The date of adaptive reuse is different
4. Different new functions for adaptive reuse

The Meridian Gate is the main gate of the Forbidden City in Beijing and is adaptive reused as an exhibition hall. The project won the UNESCO Cultural Heritage Protection Award in 2004. A modern exhibition hall is built in the Meridian Gate of the Forbidden City, which makes the traditional architectural space meet the standard requirements of modern international exhibitions on the basis of full protection of cultural relics, highlights the historical value of cultural relics, and is a model for the reuse of architectural heritage. The Duan Gate, between the Meridian Gate and the Tiananmen Gate, is adaptive reused as a cultural relics warehouse and exhibition hall. The Zhengyang Gate is located at the southernmost end of Tiananmen Square on the north–south central axis of Beijing, and is the only well-preserved gate in Beijing. It is adaptive reused as Beijing Folk Custom Exhibition Hall. Both the Forbidden City and the Temple of Heaven are world cultural heritage and are adaptive reused as museums and parks. The Xiannong Temple is reused as the Beijing Ancient Architecture Museum, which is the first architectural thematic museum in China. Qianmen Street, Nanluogu Lane and Tianqiao South Street are now reused as historical and cultural blocks with comprehensive functions. Their functions are different in the past, including commercial, residential and cultural functions.

Step 3. The weight of each element and index is determined by expert scoring, analytic hierarchy process

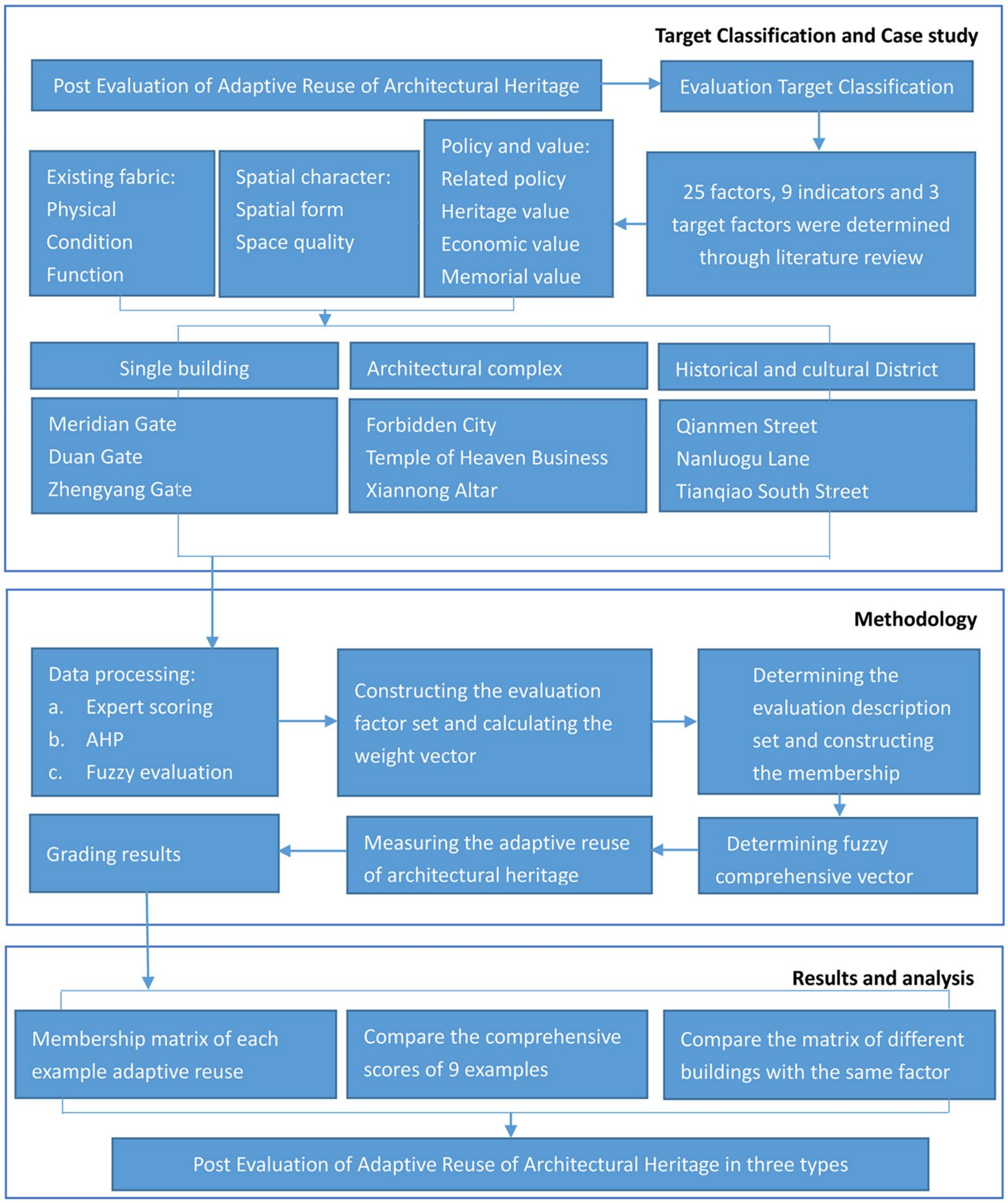

Fig. 1 Overview of research

(AHP) and fuzzy evaluation (Tables 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17).

Step 4. Through the scoring of the questionnaire survey, nine examples of the adaptive reuse of architectural heritage are evaluated. According to the local law and rules, the survey has get permission. Twenty experts described 25 factors with a score of 1–9 to form the pair-wise comparison matrix. 1–9 represents different degrees of importance, from less good to very good. These 20 experts are composed of academic experts from urban planning, urban history, architectural heritage, landscape and cultural tourism departments.

Table 2 The standard judgement matrix of the AHP

	B_1	…	B_j	…	B_n
B_1	B_{11}	…	B_{1j}	…	B_{1n}
…	…	…	…	…	…
B_i	B_{i1}	…	B_{ij}	…	B_{in}
…	…	…	…	…	…
B_n	B_{n1}	…	B_{nj}	…	1

Table 3 The average random consistency index RI [71]

n	1	2	3	4	5	6	7
RI	0	0	0.52	0.89	1.12	1.26	1.36

Table 4 Judgement matrix and weight of target classification

	A1	A2	A3	Weight	λ_{max}	CR value
A1	1	1	1.5	0.375	3	0
A2	1	1	1.5	0.375		
A3	1/1.5	1/1.5	1	0.25		

Table 5 Judgement matrix and weight of existing fabric

	B1	B2	B3	Weight	λ_{max}	CR value
B1	1	1/4	5	0.2311	3.0713	0.0686
B2	4	1	9	0.7085		
B3	1/5	1/9	1	0.0603		

Table 6 Judgement matrix and weight of spatial character

	B4	B5	Weight	λ_{max}	CR value
B4	1	1/5	0.1667	2	0
B5	5	1	0.8333		

They are familiar with Beijing's historical and cultural heritage and have been engaged in relevant work for more than 5 years. The data obtained are multiplied by the weight of the indicators, and converted into the percentile system to obtain the grade and score of each architectural heritage adaptive reuse (Tables 19, 20, 21).

As for the evaluation of the adaptive reuse of architectural heritage, the common quantitative research methods include analytic hierarchy process, fuzzy evaluation method and structural model equation [67]. Analytic Hierarchy Process (AHP) decomposes the elements related to decision-making into objectives, criteria, schemes and other levels. It is a hierarchical weight decision analysis method combining qualitative and quantitative methods [68]. But its disadvantage is that

Table 7 Judgement matrix and weight of policy and value

	B6	B7	B8	B9	Weight	λ_{max}	CR value
B6	1	1/3	1/2	1/5	0.0838	4.0511	0.0191
B7	3	1	2	1/3	0.2323		
B8	2	1/2	1	1/4	0.1377		
B9	5	3	4	1	0.5462		

Table 8 Judgement matrix and weight of physical condition

	*u*1	*u*2	*u*3	*u*4	*u*5	Weight	λ_{max}	CR value
*u*1	1	4	3	7	5	0.4932	5.2622	0.0585
*u*2	1/4	1	1/2	3	2	0.1418		
*u*3	1/3	2	1	4	2	0.2083		
*u*4	1/7	1/3	1/2	1	1/2	0.0630		
*u*5	1/5	1/2	1/2	2	1	0.0938		

Table 9 Judgement matrix and weight of function

	*u*6	*u*7	*u*8	Weight	λ_{max}	CR value
*u*6	1	3	2	0.5396	3.0092	0.0088
*u*7	1/3	1	1/2	0.1634		
*u*8	1/2	2	1	0.2969		

Table 10 Judgement matrix and weight of update part

	*u*9	*u*10	*u*11	Weight	λ_{max}	CR value
*u*9	1	3	1/3	0.2583	3.0385	0.0371
*u*10	1/3	1	1/5	0.1047		
*u*11	3	5	1	0.6370		

Table 11 Judgement matrix and weight of spatial form

	*u*12	*u*13	*u*14	*u*15	Weight	λ_{max}	CR value
*u*12	1	1/2	2	1/2	0.1818	4	0
*u*13	2	1	4	1	0.3636		
*u*14	1/2	1/4	1	1/4	0.0909		
*u*15	2	1	4	1	0.3636		

Table 12 Judgement matrix and weight of space quality

	*u*16	*u*17	Weight	λ_{max}	CR value
*u*16	1	1/3	0.25	2	0
*u*17	3	1	0.75		

when there are too many indicators, the data statistics are large [69]. Fuzzy comprehensive evaluation method is a comprehensive evaluation method based on fuzzy mathematics. It uses fuzzy mathematics to make an overall evaluation of things or objects subject to various factors. It has the characteristics of clear and systematic results, and can better solve the fuzzy and difficult to quantify problems [70]. The structural equation model is a quantitative study of the relationship between multiple variables. In this study, there are many indicators and a large amount of data for the post-evaluation of the reuse of architectural heritage. Therefore, the combination of AHP and fuzzy evaluation can make a comprehensive evaluation of things affected by multiple factors, with clear results. The membership theory of fuzzy mathematics transforms qualitative evaluation into quantitative evaluation.

The method of this study will transform qualitative evaluation into quantitative evaluation through six steps. (1) Constructing the evaluation factor set. There are 25 factors in total. (2) Calculating the weight vector (3) Determining the evaluation description set. (4) Constructing the membership matrix. (5) Determining the fuzzy comprehensive evaluation vector. (6) Measuring the adaptive reuse of architectural heritage. Through these six steps, the qualitative evaluation of 25 influencing factors in the post-use evaluation of the adaptive reuse of architectural heritage will be transformed into quantitative evaluation.

Table 13 Judgement matrix and weight of related policy

	*u*18	*u*19	*u*20	Weight	λ_{max}	CR value
*u*18	1	1/3	1/3	0.1429	3	0
*u*19	3	1	1	0.4286		
*u*20	3	1	1	0.4286		

Table 14 Judgement matrix and weight of economic value

	*u*22	*u*23	Weight	λ_{max}	CR value
*u*22	1	1/2	0.3333	2	0
*u*23	2	1	0.6667		

Table 15 Judgement matrix and weight of memorial value

	*u*24	*u*25	Weight	λ_{max}	CR value
*u*24	1	1/3	0.25	2	0
*u*25	3	1	0.75		

Evaluation method

Fuzzy comprehensive evaluation method is a comprehensive evaluation method based on fuzzy mathematics. This comprehensive evaluation method transforms qualitative evaluation into quantitative evaluation according to the membership theory of fuzzy mathematics, that is, fuzzy mathematics is used to make an overall evaluation of things or objects restricted by many factors. In this paper, the fuzzy comprehensive evaluation method is used to measure the adaptive reuse of architectural heritages, and the 6 evaluation steps are taken as follows:.

1. Constructing the evaluation factor set U. The evaluation factor set U is composed of 25 factors (Eq. 1) and the factor i is represented by u_i.

$$U = \{u_1, u_2, \ldots, u_{25}\} \tag{1}$$

2. Calculating the weight vector. The weights of factors represent the different effects on the adaptive reuse of architectural heritage. The weight vector W consists of the weights of 25 factors and w_i represent the weight of factor i, and $\sum_{i=1}^{25} w_i = 1$ (Eq. 2).

$$W = [w_1, w_2, \ldots, w_{25}] \tag{2}$$

The weight w_i is determined by the analytic hierarchy process (AHP). First, the pair-wise comparison matrices are determined by experts using a scale from 1 to 9 to judge the relative importance of each indicator, from the least important to the most important.

Table 16 Weights of target A, index B and factor u

Target	Weight	Index	Weight	Factor	Weight	Comprehensive weight
A1	0.375	B1	0.2311	*u*1	0.4932	0.0427
				*u*2	0.1418	0.0123
				*u*3	0.2083	0.0181
				*u*4	0.0630	0.0055
				*u*5	0.0938	0.0081
		B2	0.7085	*u*6	0.5396	0.1434
				*u*7	0.1634	0.0434
				*u*8	0.2969	0.0789
		B3	0.0603	*u*9	0.2583	0.0058
				*u*10	0.1047	0.0024
				*u*11	0.6370	0.0144
A2	0.375	B4	0.1667	*u*12	0.1818	0.0114
				*u*13	0.3636	0.0227
				*u*14	0.0909	0.0057
				*u*15	0.3636	0.0227
		B5	0.8333	*u*16	0.2500	0.0781
				*u*17	0.7500	0.2344
A3	0.25	B6	0.0838	*u*18	0.1429	0.0030
				*u*19	0.4286	0.0090
				*u*20	0.4286	0.0090
		B6	0.2323	*u*21	1	0.0581
		B7	0.1377	*u*22	0.3333	0.0115
				*u*23	0.6667	0.0230
		B8	0.5462	*u*24	0.2500	0.0341
				*u*25	0.7500	0.1024

Table 17 Evaluation grades and description

Grades	Description of grades	Score
Excellent	Most of the factors extremely meet the reuse requirements, and the architectural heritages have high reusability	100–85
Good	Most of the factors meet the reuse requirements, and the architectural heritages have good reusability	84–70
Moderate	Some of the factors meet the reuse requirements, and the architectural heritages have general reusability	69–55
Poor	Most of the factors could not meet the reuse general requirements, and the architectural heritages have low reusability	54–0

The standard judgement matrix is shown in Table 2, where $B_{ij} = 1/B_{ji}$, $B_{ii}=1$. Second, the principal eigenvalue λ_{max} is calculated for each judgement matrix, and the corresponding eigenvector is obtained to show the relative weights among the indicators. Then, the consistency index CI is calculated. Finally, we checked the consistency ratio CR of the result by comparing it with the average random consistency index RI. The RI value usually does not need to be calculated and can be obtained from Table 3 of the average random consistency index. The consistency ratio CR less than or equal to 0.1 is acceptable; otherwise, it is necessary to revise the subjective judgement until the appropriate ratio is achieved. The consistency index CI is calculated using the Eq. (3) and the consistency ratio CR is calculated using the Eq. (4).

$$CI = \frac{\lambda_{\max} - n}{n-1} \tag{3}$$

$$CR = \frac{CI}{RI} \tag{4}$$

The judgement matrices are constructed by twenty experts from academic professionals in urban planning, history, architectural history, landscape, and cultural tourism department as shown in Tables 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14 and 15, and the weights of the targets, the index and the factors were respectively determined by computing the principal eigenvalue λ_{max} and its corresponding eigenvector of each judgement matrix. Through the computation, all consistency ratio CRs were less than 0.1.

After the comparative analysis and calculation, the weights of target A, index B and factor u were obtained as shown in Table 16. The comprehensive weight w_i was calculated as follows:

$$\begin{aligned} &\text{comprehensive weight } w_i \text{ of factor } u_i \\ &\quad = (\text{weight of factor } u_i) \\ &\qquad \times (\text{weight of index attached to } u_i) \\ &\qquad \times (\text{weight of target attached to } u_i) \end{aligned} \tag{5}$$

According to Eq. (5), the weight vector W was calculated as follows:

$$\begin{aligned} W = [&0.0427, 0.0123, 0.0181, 0.0055, 0.0081, \\ &0.1434, 0.0434, 0.0789, 0.0058, 0.0024, \\ &0.0144, 0.0114, 0.0227, 0.0057, 0.0227, \\ &0.0781, 0.2344, 0.0030, 0.0090, 0.0090, \\ &0.0581, 0.0115, 0.0230, 0.0341, 0.1024] \end{aligned} \tag{6}$$

3. Determining the evaluation description set. The evaluation description set V is used with 4 levels from excellent to poor for each factor u_i.

$$V = \{\text{Excellent, Good, Moderate, Poor}\} \tag{7}$$

4. Constructing the membership matrix. The membership degree of the factor u_i is counted according to questionnaire with the help of the evaluation description set. When the evaluation object k is judged by the factor u_i, the membership degree of the factor u_i in evaluation description v_j is r_{ij}. Then, the fuzzy evaluation vector R_i^k for the evaluation object k by factor u_i is represented as $R_i^k = \left[r_{i1}^k, r_{i2}^k, r_{i3}^k, r_{i4}^k\right]$, and the membership matrix R^k for the evaluation object k can be expressed as follows:

$$R^k = \begin{bmatrix} r_{1,1}^k & r_{1,2}^k & r_{1,3}^k & r_{1,4}^k \\ r_{2,1}^k & r_{2,2}^k & r_{2,3}^k & r_{2,4}^k \\ \vdots & \vdots & \vdots & \vdots \\ r_{25,1}^k & r_{25,2}^k & r_{25,3}^k & r_{25,4}^k \end{bmatrix} \tag{8}$$

5. Determining the fuzzy comprehensive evaluation vector. The fuzzy comprehensive evaluation vector C^k for the evaluation object k is obtained by multiplying the weight vector W and the membership matrix R^k.

$$\begin{aligned} C^k = W \cdot R^k &= [w_1, w_2, \ldots, w_{25}] \cdot \begin{bmatrix} r_{1,1}^k & r_{1,2}^k & r_{1,3}^k & r_{1,4}^k \\ r_{2,1}^k & r_{2,2}^k & r_{2,3}^k & r_{2,4}^k \\ \vdots & \vdots & \vdots & \vdots \\ r_{25,1}^k & r_{25,2}^k & r_{25,3}^k & r_{25,4}^k \end{bmatrix} \\ &= \left[c_1^k, c_2^k, c_3^k, c_4^k\right] \end{aligned} \tag{9}$$

6. Measuring the adaptive reuse of architectural heritage. The comprehensive evaluation results are expressed in the percentile system. The score vector P corresponding to the evaluation description set is expressed as $P = [92.5, 77, 62, 27]^T$, and the evaluation index score is expressed as follows:

$$S = C^k \cdot P \quad (10)$$

Through the above six steps of fuzzy calculation process, the evaluation score S is obtained, and the evaluation grades and descriptions of architectural heritages are consulted in Table 17.

Results

In this study, 9 architectural heritages on the central axis of Beijing were selected as examples (Table 18). The central axis of Beijing is rich in historical resources, and is the core area of Beijing's urban spatial structure, which dominates the urban function and spatial pattern. The central axis of Beijing is applying for the world cultural heritage, and the protection and adaptive reuse of its heritage buildings are particularly concerned. This research divides its architectural heritage into three types. The first type is a single building. Three typical examples are the Meridian Gate, the Duan Gate and the Zhengyang Gate, which are all adaptive reused as exhibition halls. The second type is the architectural complex. Three typical examples are the Forbidden City, the Temple of Heaven and the Xiannong Temple. The Forbidden City in Beijing, formerly known as the Forbidden City, is the imperial palace of the Ming and Qing dynasties in China. It is located at the center of the central axis of Beijing. It is one of the largest and best preserved ancient wooden structures in the world, and is reused as a museum for sightseeing. In the Ming and Qing dynasties, the Temple of Heaven was a place for emperors to worship the emperor and pray for a bumper harvest of grain. Now it is reused as a historical park. The Xiannong Altar is an important place for the emperors of the Ming and Qing dynasties to worship mountains, rivers, Shennong and other gods. It is the highest level, largest scale and most complete ancient sacrificial farm in China. It was once reused as a school, library and stadium, and is now the Beijing Museum of Ancient Architecture. The third type is the historical and cultural block. The historical and cultural block is an area where a large number of residents live. It is a living cultural heritage with its unique community culture. It not only protects the body of those historical buildings, but also preserves the culture it carries, protects the content of intangible forms, and preserves cultural diversity. Maintain community tradition, improve living environment and promote regional economic vitality. Qianmen Street, Nanluogu Lane and Tianqiao South Street are protected and reused as historical and cultural blocks.

Taking Meridian Gate as example, the membership matrix *R* was counted as shown in Table 19 according to the questionnaire for Meridian Gate. The fuzzy comprehensive evaluation vector *C* for the Meridian Gate is obtained by multiplying the weight vector W and the membership matrix *R*. Through calculation, The fuzzy comprehensive evaluation vector *C* equals to [0.8529, 0.1153, 0.0157, 0.0162]. Finally, the evaluation index score is 89.18 according to the Eq. (10) and the adaptive reuse of Meridian Gate belongs to the "Excellent" level.

In the same way, we calculated the evaluation index scores for the adaptive reuse of other architectural heritages. The calculation results were 80.25 (C^2 = [0.5556, 0.1253, 0.3030, 0.0158]) for Duan Gate, 67.26 (C^3 = [0.4271, 0.1124, 0.1903, 0.2702]) for Zhengyang Gate, 90.50 (C^4 = [0.8913, 0.0884, 0.0200, 0.0003]) for Forbidden City, 89.46 (C^5 = [0.8707, 0.0961, 0.0177, 0.0158]) for Temple of Heaven, 84.77 (C^6 = [0.5150, 0.4715, 0.0132, 0.0003]) for Xiannong Altar, 91.03 (C^7 = [0.9120, 0.0804, 0.0077, 0]) for Qianmen Street, 81.69 (C^8 = [0.3644, 0.6066, 0.0132, 0.0165]) for Nanluogu

Table 18 General information of examples and evaluation grades

Type	Heritage buildings	Date of constriction	Date of reuse	New function	Grades
Single building	Meridian gate	About 1420	About 2005	Exhibition hall	Excellent
	Duan gate	About 1420	About 1949	Cultural Relics Warehouse and Exhibition Hall	Good
	Zhengyang gate	About 1420	About 1985	Beijing Folk Custom Exhibition Hall	Moderate
Architectural complex	Forbidden City	About 1420	About 1925	The Palace Museum	Excellent
	Temple of Heaven	About 1420	About 1949	Temple of Heaven Park	Excellent
	Xiannong Altar	About 1420	About 2000	Beijing Museum of Ancient Architecture	Good
Historical and cultural district	Qianmen street	About 1420	About 1965	Historical and Cultural Block	Excellent
	Nanluogu Lane	About 1750	About 2000	Historical and Cultural Block	Good
	Tianqiao South Street	About 1560	About 1957	Historical and Cultural Block	Moderate

Table 19 Membership matrix of single building adaptive reuse

	Meridian gate				Duan gate				Zhengyang gate			
	Excellent	**Good**	**Moderate**	**Poor**	**Excellent**	**Good**	**Moderate**	**Poor**	**Excellent**	**Good**	**Moderate**	**Poor**
Location	0.79	0.14	0.06	0.01	0.21	0.34	0.56	0	0.11	0.14	0.16	0.59
Facade features	0.97	0.03	0	0	0.96	0.03	0.01	0	0.96	0.03	0.01	0
Material	0.83	0.12	0.05	0	0.82	0.11	0.07	0	0.32	0.11	0.07	0.50
Structure system	0.92	0.08	0	0	0.90	0.05	0.05	0	0.90	0.05	0.05	0
Construction techniques	0.89	0.10	0.01	0	0.80	0.10	0.10	0	0.50	0.10	0.10	0.30
Original function	0.92	0.08	0	0	0.82	0.08	0.10	0	0.82	0.01	0.10	0.07
New function	0.51	0.43	0.06	0	0.41	0.43	0.16	0	0.01	0.43	0.16	0.40
Adding some sub-function	0.46	0.23	0.11	0.20	0.26	0.23	0.31	0.20	0.06	0.23	0.31	0.40
New materials	0.59	0.38	0.03	0	0.29	0.38	0.33	0	0.09	0.38	0.33	0.20
New techniques	0.67	0.32	0.01	0	0.57	0.32	0.11	0	0.07	0.32	0.11	0.50
New decoration	0.26	0.74	0	0	0.36	0.64	0	0	0.26	0.64	0	0.10
Main space	0.92	0.08	0	0	0.62	0.08	0.30	0	0.32	0.08	0.60	0
Traffic space	0.91	0.09	0	0	0.81	0.09	0.10	0	0.31	0.09	0.60	0
Spatial organization	0.89	0.11	0	0	0.79	0.11	0.10	0	0.29	0.21	0.10	0.40
Outdoor space	0.87	0.13	0	0	0.37	0.63	0	0	0.37	0.63	0	0
Spatial scale	0.96	0.04	0	0	0.46	0.04	0.50	0	0.26	0.04	0.50	0.20
Landscape factor	0.93	0.07	0	0	0.23	0.07	0.70	0	0.23	0.07	0.20	0.50
International charters	0.91	0.09	0	0	0.21	0.09	0.70	0	0.11	0.09	0.70	0.10
Local principles	0.87	0.13	0	0	0.97	0.03	0	0	0.97	0.03	0	0
Local laws	0.87	0.13	0	0	0.97	0.03	0	0	0.97	0.03	0	0
Historical culture and value	0.95	0.05	0	0	0.95	0.05	0	0	0.95	0.05	0	0
Decoration cost	0.88	0.12	0	0	0.98	0.02	0	0	0.98	0.02	0	0
Reuse income	0.76	0.21	0.03	0	0.56	0.21	0.23	0	0.06	0.21	0.23	0.50
Memory information	0.98	0.02	0	0	0.78	0.02	0.20	0	0.78	0.02	0.10	0.10
Cultural content	0.95	0.05	0	0	0.90	0	0.05	0	0.60	0.05	0.15	0.20
Evaluation index score	89.18				80.25				67.26			

Lane, 57.13 ($C^9 = [0.2893, 0.1050, 0.1877, 0.3945]$) for Tianqiao South Street.

Existing fabric is the characteristics of the building itself, including the physical characteristics, functional characteristics and updating parts of the building. It can be seen from the data that the location score of 9 historical sites is high, and the location determines the accessibility, which is the basis for adaptive reuse. Nine historical sites are located on the central axis of Beijing, which is the core area of the city. In terms of physical characteristics, the scores of individual buildings, building groups and historical and cultural blocks are similar, but there are great differences in functions. The available functions of individual buildings are single. For example, the Meridian Gate, Duan Gate and Zhengyang Gate are only adaptive reused as exhibition halls or warehouses. The functional characteristics of the architectural complex and historical and cultural blocks are highly rated, and these relics are comprehensively used as parks, exhibitions and other functions. Among them, the Forbidden City has the highest function score, which shows that people have the best evaluation on the adaptive reuse of the Forbidden City. In the function score, the lowest is Zhengyang Gate. Although the location score of Zhengyang Gate is high, it is rarely visited in the process of reuse. The score of the Update part is high for historical and cultural blocks and architectural complex. It can be seen that new materials, new technologies and new decorations of building recycling are applied in this type. In a word, Existing fabric is closely related to the physical properties of the building itself and the newly added parts for adaptive reuse. The content with low score also needs to be improved in the future reuse.

As for the evaluation of space characteristics, the project includes space form and space quality. The form and quality of space can give users the most intuitive feeling. It can be seen from the data that the heritage buildings of the architectural complex type have the highest scores in space form and space quality, that is, the reuse space of the Forbidden City, the Temple of Heaven and the Xiannong Altar has a high score. The single building has a high score in the main space, and the lowest score in the landscape factor. Similar sites in historical and cultural blocks have the highest score in outdoor space, but low score in traffic space. Therefore, more attention should be paid to the construction of traffic space in the next adaptive reuse process.

The third target layer is policy and value. Policies include international regulations and local policies, and values include heritage values, economic values and memory values. The Forbidden City, Temple of Heaven and Meridian Gate scored the highest in this project. The lower scores are Zhengyangmen and Tianqiao South Street, which shows that the reuse of these two heritages does not fully reflect their heritage value, economic value and memory value.

Discussion and limitations

In this study, the analytic hierarchy process and fuzzy evaluation method are used to post-evaluation on the adaptive reuse of historical buildings. This paper constructs a quantitative research framework for the post-evaluation of adaptive reuse of historical buildings. The results show that the Meridian Gate, the Forbidden City and Qianmen Street are the projects with the highest total score among the three types. Zhengyangmen and Tianqiao South Street are the two projects that need to be improveed most.

In the evaluation of three single buildings, Meridian Gate has the highest total score. Among the 25 factors of the Meridian Gate, Facade features has the highest evaluation (Table 19), indicating that the facade design method of the reuse project is appropriate. While maintaining the original historical information of the facade, the air-conditioning equipment is hidden in the facade components, which does not affect the historical characteristics of the building. The design of the project will not adversely affect the ancient buildings; The structure is reversible, that is, if removed, the ancient building can be restored to its original state; The interior of the exhibition hall is modern, and at the same time, the audience can also appreciate the beauty of ancient buildings in the exhibition hall, so as to achieve the synchronous display of cultural relics and ancient buildings. However, the factor of adding some sub-function of Meridian Gate is the lowest, indicating that the reuse function of Meridian Gate is single and only used as exhibition hall. Wang J believes that the architectural heritage should be used with multiple functions to maximize its service to the present [72]. The highest scoring factor of the Forbidden City is Spatial organization (Table 20), which shows that the combination of building groups is the most important factor in the reuse of building groups. Kee T believes that the combination of building groups determines the indoor and outdoor space characteristics of the building, and thus determines the function of building heritage reuse [31]. The Qianmen Street has the highest score in the type of historical and cultural district. From the membership matrix of each factor (Table 21), Location and Main space are the two factors with the highest score. It can be seen that the location and main space form of the Qianmen Street are the most important reasons for its popularity.

For the two projects with the lowest score, the membership matrix of Zhengyang Gate shows that its new function has the lowest evaluation (Table 19), indicating that the selection of its reuse function is not reasonable. The function of reuse of architectural heritage is its new role in urban development. It maintains the continuity of urban historical development and integrates architectural heritage into economic, social and cultural development again, becoming a part of common development with the city [73]. Therefore, the choice of function is very important. The membership matrix of Tianqiao South Street shows that its cultural content has the lowest score (Table 21), indicating the lack of expression of cultural content in its reuse design. The cultural content is the key to maintain the continuity of the reuse of historical architectural heritage. The cultural heritage should be highlighted in the historical architectural heritage so that it can display the continuity of the integration of historical culture and modern culture [26]. It can also be seen that for the adaptive reuse of single buildings, the most important thing is the building facades and diversity of functions. For the adaptive reuse of building complex, the most important thing is the combination of architectural space. The most important thing for the adaptive reuse of historical district types is the expression of the overall cultural content in the main spatial form of the block.

In the current research on the reuse of historical buildings, the facade, structure, materials and functions of the buildings in the case of single buildings are the main focus of attention. How to combine these aspects with modernization without affecting the form of historical information has always been the difficulty and innovation point of the reuse of single buildings. For building complex, the facades and structures of individual buildings are also important, but the outdoor space has become the focus of reuse design. For the historical district, the form of the street is the most concerned content, and how to combine the historical form of the street with the modern functional requirements is the focus. In addition, we should pay attention to the complete protection of various factors such as space, humanity and natural environment while paying attention to the historical architectural heritage in the building itself. The characteristics of the times and valuable material remains formed in the historical evolution process of the architectural heritage

Table 20 Membership matrix of architectural complex adaptive reuse

	Forbidden city				Temple of heaven				Xiannong altar			
	Excellent	Good	Moderate	Poor	Excellent	Good	Moderate	Poor	Excellent	Good	Moderate	Poor
Location	0.79	0.04	0.16	0.01	0.80	0.14	0.06	0	0.14	0.85	0	0.01
Facade features	0.98	0.02	0	0	0.97	0.03	0	0	0.97	0.03	0	0
Material	0.93	0.02	0.05	0	0.83	0.17	0	0	0.83	0.12	0.05	0
Structure system	0.99	0.01	0	0	0.92	0.08	0	0	0.92	0.08	0	0
Construction techniques	0.99	0	0.01	0	0.89	0.10	0.01	0	0.89	0.10	0.01	0
Original function	0.92	0.08	0	0	0.92	0.08	0	0	0.92	0.08	0	0
New function	0.51	0.43	0.06	0	0.91	0.03	0.06	0	0.11	0.83	0.06	0
Adding some sub-function	0.66	0.23	0.11	0	0.46	0.23	0.11	0.20	0.46	0.43	0.11	0
New materials	0.79	0.18	0.03	0	0.50	0.38	0.12	0	0.59	0.38	0.03	0
New techniques	0.87	0.12	0.01	0	0.57	0.42	0.01	0	0.67	0.32	0.01	0
New decoration	0.86	0.14	0	0	0.26	0.54	0.21	0	0.26	0.74	0	0
Main space	0.92	0.08	0	0	0.92	0.08	0	0	0.52	0.48	0	0
Traffic space	0.91	0.09	0	0	0.90	0.10	0	0	0.61	0.39	0	0
Spatial organization	0.99	0.01	0	0	0.89	0.11	0	0	0.79	0.21	0	0
Outdoor space	0.97	0.03	0	0	0.88	0.12	0	0	0.87	0.13	0	0
Spatial scale	0.96	0.04	0	0	0.97	0.03	0	0	0.46	0.54	0	0
Landscape factor	0.93	0.07	0	0	0.93	0.07	0	0	0.43	0.57	0	0
International charters	0.51	0.49	0	0	0.91	0.09	0	0	0.91	0.09	0	0
Local principles	0.97	0.03	0	0	0.87	0.13	0	0	0.87	0.13	0	0
Local laws	0.97	0.03	0	0	0.87	0.13	0	0	0.87	0.13	0	0
Historical culture and value	0.99	0.01	0	0	0.95	0.05	0	0	0.45	0.55	0	0
Decoration cost	0.98	0.02	0	0	0.88	0.12	0	0	0.88	0.12	0	0
Reuse income	0.86	0.11	0.03	0	0.76	0.24	0	0	0.76	0.21	0.03	0
Memory information	0.98	0.02	0	0	0.98	0.02	0	0	0.28	0.72	0	0
Cultural content	0.95	0.05	0	0	0.95	0.05	0	0	0.25	0.75	0	0
Evaluation index score	90.50				89.46				84.77			

should be respected. Historic architectural heritage, residents and natural environment together constitute the urban ecological balance system. So as to achieve the balance between economic, ecological and urban objectives, and promote the overall system and balanced and sustainable development. The reuse of historical buildings should be based on the actual situation in the process of urban sustainable development, and the reuse strategy suitable for historical architectural heritage should be selected to make it truly become the new vitality of the part of urban sustainable development.

In addition, this study is conducive to improving the scientific level of decision-making on the adaptive reuse of architectural heritage. By establishing a perfect post-project evaluation system and scientific method system, on the one hand, it can enhance the sense of responsibility of the former appraisers, urge the appraisers to do a good job in the pre-project evaluation of the adaptive reuse of architectural heritage, and improve the accuracy of the project evaluation, especially the selection and decision-making of the functions of the reuse of architectural heritage; On the other hand, the problems in project decision-making can be corrected in time through the feedback information of post-project evaluation, so as to improve the scientific level of project decision-making. Compared with the current research on the adaptive reuse evaluation of historical buildings, our main contribution is the comprehensive application of quantitative methods after the adaptive reuse of historical buildings. It fills the gap in the research framework of quantitative evaluation of the adaptive reuse of historical buildings. More importantly, through the calculation of factors and indicator weights, it is easy to find low sub items and find the content to be improved. Of course, these factors can also be used for the evaluation before the adaptive reuse of historical buildings, which is a dynamic process.

However, this method also has defects. It can only evaluate existing factors, improve existing factors, and cannot provide new solutions for decision-making. When we hope to solve more general problems, the number of indicators will probably increase. The

Table 21 Membership matrix of historical and cultural district adaptive reuse

	Qianmen street				Nanluogu lane				Tianqiao south street			
	Excellent	Good	Moderate	Poor	Excellent	Good	Moderate	Poor	Excellent	Good	Moderate	Poor
Location	0.79	0.15	0.06	0	0.99	0.01	0	0	0.11	0.14	0.66	0.09
Facade features	0.97	0.03	0	0	0.27	0.73	0	0	0.26	0.03	0.01	0.70
Material	0.83	0.12	0.05	0	0.83	0.12	0.05	0	0.32	0.11	0.07	0.50
Structure system	0.92	0.08	0	0	0.92	0.08	0	0	0.90	0.05	0.05	0
Construction techniques	0.89	0.10	0.01	0	0.39	0.60	0.01	0	0.50	0.10	0.10	0.30
Original function	0.92	0.08	0	0	0.22	0.78	0	0	0.52	0.01	0.10	0.37
New function	0.91	0.03	0.06	0	0.51	0.43	0.06	0	0.21	0.23	0.16	0.40
Adding some sub-function	0.96	0.03	0.01	0	0.16	0.53	0.11	0.20	0.06	0.23	0.21	0.20
New materials	0.99	0.01	0	0	0.59	0.38	0.03	0	0.09	0.38	0.33	0.20
New techniques	0.67	0.32	0.01	0	0.67	0.32	0.01	0	0.07	0.32	0.11	0.50
New decoration	0.26	0.74	0	0	0.26	0.74	0	0	0.26	0.64	0	0.10
Main space	0.92	0.08	0	0	0.42	0.58	0	0	0.32	0.08	0.60	0
Traffic space	0.91	0.09	0	0	0.11	0.88	0	0.01	0.31	0.09	0.60	0
Spatial organization	0.89	0.11	0	0	0.19	0.91	0	0	0.29	0.21	0.10	0.40
Outdoor space	0.87	0.13	0	0	0.17	0.81	0	0.02	0.37	0.63	0	0
Spatial scale	0.96	0.04	0	0	0.96	0.04	0	0	0.26	0.04	0.50	0.20
Landscape factor	0.93	0.07	0	0	0.13	0.87	0	0	0.23	0.07	0.20	0.50
International charters	0.91	0.09	0	0	0.11	0.89	0	0	0.11	0.09	0.70	0.10
Local principles	0.87	0.13	0	0	0.87	0.13	0	0	0.67	0.13	0	0.20
Local laws	0.87	0.13	0	0	0.87	0.13	0	0	0.87	0.13	0	0
Historical culture and value	0.95	0.05	0	0	0.65	0.35	0	0	0.83	0.04	0.01	0.12
Decoration cost	0.88	0.12	0	0	0.88	0.12	0	0	0.98	0.02	0	0
Reuse income	0.76	0.21	0.03	0	0.76	0.21	0.03	0	0.06	0.21	0.23	0.50
Memory information	0.98	0.02	0	0	0.18	0.82	0	0	0.08	0.02	0	0.90
Cultural content	0.95	0.05	0	0	0.15	0.85	0	0	0.01	0.05	0.02	0.92
Evaluation index score	91.03				81.69				57.13			

increase of indicators means that we need to construct a judgment matrix with deeper level, more quantity and larger scale. Then we need to compare many indicators in pairs. Generally, we use 1 to 9 to illustrate the relative importance of the AHP in comparison with each other. If there are more and more indicators, it may be difficult to judge the importance of each two indicators, and even affect the consistency of the single ranking and the total ranking of the hierarchy, making the consistency test fail. If it fails, it needs to be adjusted. It is difficult to adjust when the number of indicators is large.

In the process of research, we found some deficiencies, which are worth further study: (1) The adaptive reuse of historical buildings is a dynamic process, so the evaluation indicators are not static whether before or after adaptive reuse. (2) We have selected three types, 9 historical sites in total, and more cases need comparative study and analysis. (3) We should make a comparative study on the evaluation of historical buildings before adaptive reuse and after use.

This study has established a comprehensive quantitative evaluation system for the post evaluation of the adaptive reuse of historical buildings. This framework can be used to calculate the importance of each factor and improve each low item. In the future research, the feelings of different groups should be added.

Conclusions

This study proposes a post-evaluation framework and method for the adaptive reuse of historical buildings, and selects three types: single buildings, architectural complexes and historical and cultural districts. In the case study, 9 historical sites on the central axis of Beijing were analyzed, and the evaluation indicators were determined through literature review, and the evaluation was conducted through the analytic hierarchy process and fuzzy evaluation method. The results show that the comprehensive score of the adaptive reuse of the Meridian Gate is the highest among the single buildings due to its appropriate new functions and the new design of the exhibition hall. Due to its historical value and spatial combination, the Forbidden City is the highest among the adaptive reuse categories of the architectural complexes. Qianmen Street is the highest among the historical and cultural districts because of its location and street combination. This study provides evaluation methods and ideas for the post-adaptive reuse of different types of historical buildings. Different types of historical buildings have different spatial characteristics. The scores are only compared in the same type of buildings. In addition, this study serves for the sustainable evaluation, optimization and sustainable development of the adaptive reuse of historical buildings. And it also finds the indicators that need to be improved for the adaptive reuse of architectural heritage.

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Author contributions
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Declarations

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