

<https://doi.org/10.1038/s40494-026-02323-y>

Minimum intervention level decision for historical buildings: historical buildings along the central axis of Beijing, China

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Historical buildings are important symbols of urban characteristics and context, and their protection or reuse requires minimal intervention. This article aims to establish a method for selecting the minimum intervention level. Firstly, this study constructed a minimum intervention method selection evaluation framework for historical buildings through literature analysis. Secondly, select 14 historical buildings along the central axis of Beijing. This study uses the Analytic Hierarchy Process to calculate the weights of evaluation indicators. And calculate the minimum intervention selection level through Fuzzy Comprehensive Evaluation. The results showed that 14 historical buildings were divided into four categories in a ratio of 2:1:10:1, and a minimum intervention strategy was proposed. This result also confirms that the intervention methods for 14 historical buildings along the central axis of Beijing are all minimal interventions. The minimum intervention system provides a scientific decision-making framework and basis for the repeated reuse of historical buildings.

With the acceleration of urbanization, the protection and utilization of historical buildings have become an important issue that urgently needs to be addressed¹. Especially in cities with profound historical and cultural backgrounds, such as Beijing, the protection of historical buildings is not only related to the inheritance of cultural heritage, but also to the sustainability of urban development. As one of the representatives of world cultural heritage, the Beijing central axis has rich historical and cultural value and unique architectural style. Therefore, how to balance “authenticity protection” and “contemporary demand satisfaction” has become a key challenge, among which the principle of “minimum intervention” has been widely recognized as a basic principle².

The Italian scholar Brandi proposed the principle of minimum intervention in the 1950 s. Then, the principle of minimum intervention appeared in the Venice Charter promulgated in 1964, emphasizing that any intervention in historical buildings should be minimized in scope and intensity to avoid unnecessary damage to their historical value, material authenticity, and cultural significance³. However, the implementation of this principle faces complex challenges: historical buildings have significant differences in preservation status, historical significance, functional requirements, and environmental backgrounds, which directly lead to varying levels of intervention required. For example, severely damaged buildings may require structural reinforcement, while relatively well preserved buildings may only require daily maintenance⁴. Therefore, how to scientifically determine the “minimum intervention level” suitable for specific historical buildings has become a key issue in conservation practice -

this not only involves qualitative judgment, but also requires quantitative analysis of multiple influencing factors, and urgently needs a systematic and operable decision-making framework.

Previous research has mainly focused on methods and evaluations of minimal intervention in the protection of historical buildings⁵, classification studies of different levels of minimal intervention⁶, and supporting factors for implementing minimal intervention (Table 1). At the same time, some scholars have proposed the “intervention level” model, aimed at providing appropriate protection strategies for different types of historical buildings⁷. However, there is still a lack of systematic research on how to choose the minimum intervention level in specific practice.

This study has two main objectives: firstly, to construct a minimal intervention evaluation system for historical buildings. Targeting value evaluation, usability evaluation, and functionality evaluation as the target layers. By conducting value assessments to clarify the protection of core elements, assessing the degree of intervention through usability assessments, and combining functional assessments (adaptive reuse needs), we ensure that modern usage needs are flexibly met while protecting the authenticity and integrity of heritage, avoiding excessive intervention or functional rigidity⁸. Decompose multiple objectives (protection, safety, functionality) into quantifiable evaluation dimensions.

The second objective is to use the Analytic Hierarchy Process (AHP) and Fuzzy Comprehensive Evaluation (FCE) for comprehensive calculation to verify whether the intervention method for 14 historical buildings along the Beijing central axis is the minimum intervention. The combination of

Table 1 | Summary of previous research about minimal intervention

Content of the study	Methodology and purpose	Limitations
The Method and Evaluation of Minimal Intervention in the Protection of Historical Buildings	Propose a methodological framework for minimal intervention in the protection of historical buildings	The universality of the methodological framework needs to be verified by more cases of different types of historical buildings ⁵
	Using multi criteria decision analysis methods, combined with expert consultation and case verification, this study constructs an evaluation system for minimal intervention in cultural heritage protection, with the aim of providing objective and systematic basis for determining the degree of intervention	The determination of criterion weights involves a certain degree of subjectivity, and some qualitative indicators are difficult to quantify ⁴⁵
	This study proposes a methodology based on a multi criteria evaluation framework, which analyzes four core parameters: energy efficiency (expected efficiency improvement), compatibility (ability to protect historical building form and material characteristics), durability, and cost-effectiveness	The limitation of the research lies in the narrow coverage of the cases, which only verifies the types of brick and stone buildings ⁴⁶
Research on Minimum Intervention Classification at Different Levels	Based on the theory of heritage conservation and case analysis, determine the minimum intervention method for heritage building protection from the aspects of architectural value, damage status, and protection objectives, and provide guidance for practice	The scope of the case is limited, and the applicability of different types of heritage buildings needs further verification. Some judgment criteria have strong subjectivity ⁹
	Deconstructing the theoretical connotation of “minimal intervention” aims to construct a value oriented dynamic decision-making model that integrates material protection, socio-cultural impact, and environmental sustainability into a unified evaluation system	Although a theoretical model has been proposed, its practical operability has not been verified through full cycle tracking of specific architectural heritage projects ⁴⁷
	Systematically evaluate the current status and adaptability potential of heritage buildings, aiming to provide a dynamic decision-making framework for heritage managers	The model has not been validated for its practical operability through the full cycle application of large-scale heritage projects ⁴⁸
Supporting factors for minimal intervention implementation	Optimizing the configuration of architectural heritage reinforcement intervention through quantitative evaluation	The subjectivity of standard weight allocation in multidimensional evaluation is not clearly explained ⁴⁹

AHP-FCE can balance the scientific allocation of weights in historical building evaluation (through AHP hierarchical quantification) and the computability of fuzzy indicators (through FCE processing of subjective language), filling the limitations of a single method in complex multi-objective decision-making⁹. Compared to traditional qualitative or purely quantitative methods, the combination of the two can dynamically balance protection and utilization needs, provide verifiable conclusions that combine objective weight logic and fuzzy adaptability, and is more suitable for small sample, high uncertainty intervention evaluations¹⁰.

The innovation of this study lies in: firstly, from the perspectives of value evaluation, usability evaluation, and functionality evaluation, the minimum intervention evaluation framework for historical buildings is proposed. Secondly, the AHP-FCE method is used to calculate the minimum intervention factors for historical buildings. The third is to verify the intervention methods for 14 historical buildings along the central axis of Beijing. Decision makers can clearly identify the number of intervention levels and the factors that affect the selection of intervention levels, thereby achieving the minimum intervention choice for the project. Provide a scientific decision-making framework and theoretical basis for the repeated reuse and sustainable protection of historical buildings.

To ensure the systematicity and comprehensiveness of the literature review, the literature search in this study follows a clear standardized process, as follows: the search platform covers international mainstream academic databases, including Google Scholar, Web of Science (WOS) core collection, and China National Knowledge Infrastructure (CNKI), to balance global research results with relevant explorations in the Chinese context. The search time span is set to nearly 30 years (January 1995 to March 2025), covering the key stages of concept dissemination, theoretical deepening, and practical innovation in the field. The geographical scope focuses on the world without restricting the research area, in order to present research differences and consensus among different countries and regions. Retrieve keywords that integrate core concepts and related dimensions, corresponding to keywords such as “minimum intervention”, “intervention level”, “historical building protection”, “adaptive reuse of historical buildings”, “architectural restoration”, “historical building renewal”, “new design

in historical context”, “intervention principles for historical buildings”, and “intervention measures for historical buildings”. Through keyword combination search and topic keyword expansion, 486 literature were preliminarily obtained (Fig. 1). After strict screening, non-academic literature such as conference abstracts, news reports, and policy documents, as well as literature that is unrelated to the research topic and has been repeatedly published, were excluded. Finally, 372 valid academic literature were included, including 156 in the Web of Science database, 138 in the Google Scholar database, and 78 in the CNKI database, providing comprehensive and accurate data source support for this literature review (Fig. 2).

The literature review of this study is divided into four parts: the first part is about the limitations of the current research status. Although many achievements have been made in the study of minimal intervention in historical buildings, there are still some research limitations, mainly reflected in the following aspects: limitations in research perspectives, limitations in research objects, and limitations in research methods. The second part is the concept of “minimal intervention” and intervention levels (Fig. 3). The third part is the evaluation factors that affect the selection of intervention levels. At present, the influencing factors that affect the selection of the minimum intervention level mainly include: protection regulations, protection level, historical building value, historical building form characteristics, spatial characteristics, integrity, functionality, and other aspects. The fourth part is a comprehensive summary of previous research methods (Fig. 1). Based on the literature review of these four sections, Table 2 Fig. 3, Intervention Level and Actions, and Table 3, Minimum Intervention Level Assessment Factors for Historical Buildings, are obtained.

The first part is about the limitations of the current research status. The limitations of the research are reflected in three aspects. One limitation is the research perspective. At present, research has focused on specific intervention methods for a particular historical building, lacking comparative studies of all intervention methods in different historical buildings¹¹. Only by clarifying the number of intervention methods can we determine which one is the minimum intervention method for a certain building.

The second limitation is the limitation of the research subject. Due to the fact that most studies focus on specific buildings and overlook the

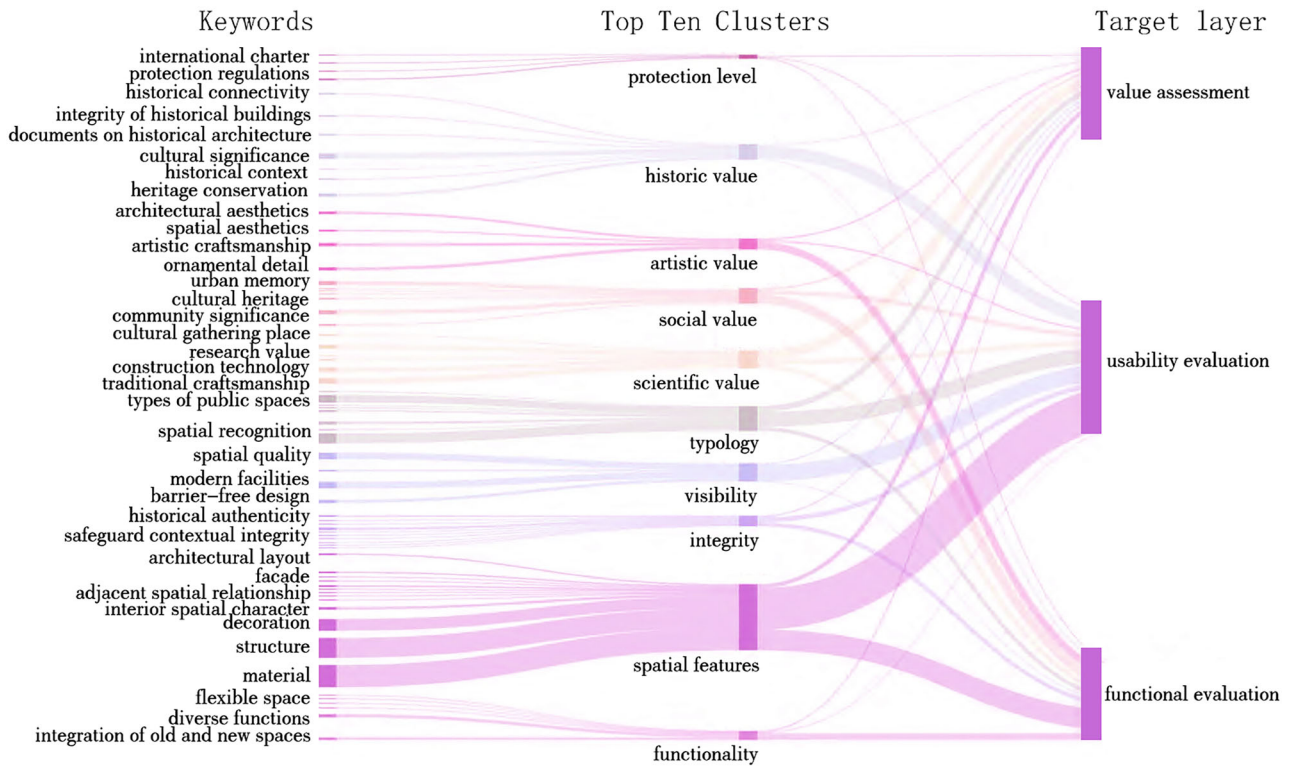


Fig. 1 | Cluster diagram and evaluation target extraction of existing research.

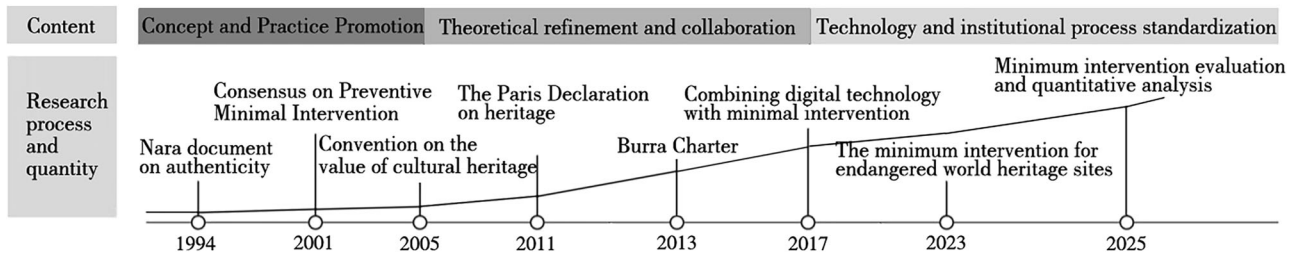


Fig. 2 | Research annual trends and paper quantity trends.

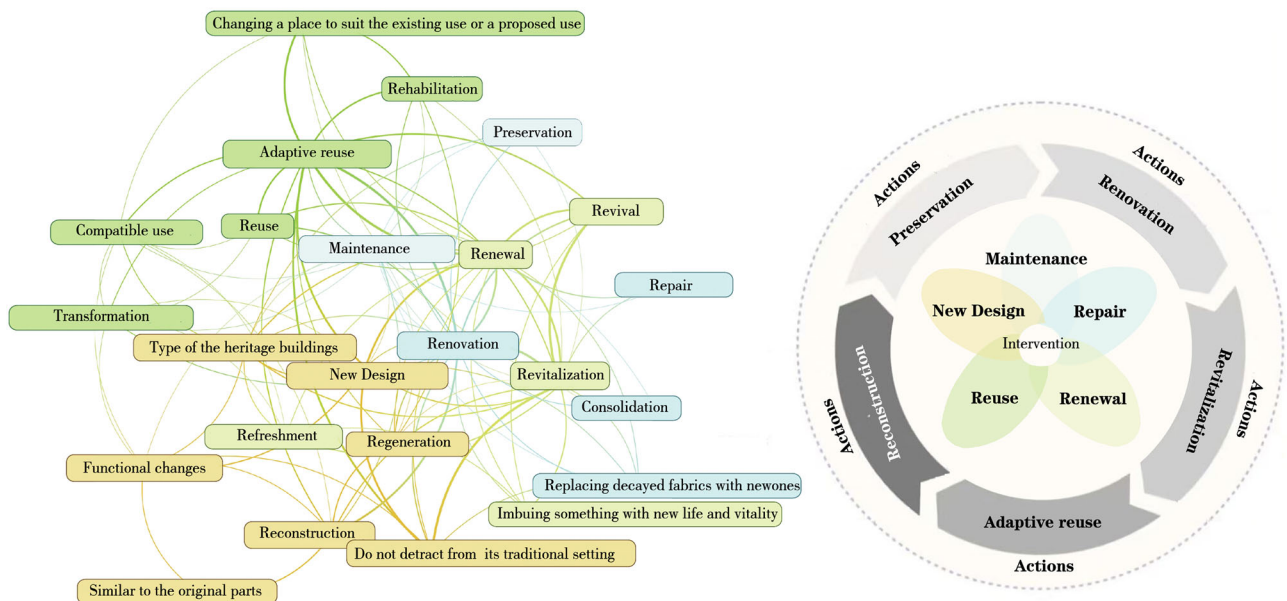


Fig. 3 | Cluster diagram and relationship diagram of intervention level.

Table 2 | Intervention level and actions

Grade	Intervention level	Intervention Actions
1	Maintenance	Preservation
2	Repair	Renovation
3	Renewal	Revitalization
4	Reuse	Adaptive reuse Compatible use
5	New Design	Reconstruction Regeneration

selection of minimal intervention methods for historical building clusters with the same cultural background, there is a lack of comparative analysis of different intervention methods for different historical buildings under the same cultural background. Although some studies have delved into the intervention methods of a particular historical building, they often overlook comparisons with other historical buildings. Comparative analysis of the same intervention level for different historical buildings can reveal the influence of different architectural forms, functions, and other aspects on the selection of intervention levels. However, such research is still relatively scarce at present. Lack of reasons: On the one hand, the selection of intervention methods for historical buildings involves multiple complex factors, including value judgments, building forms, building spaces, building functions¹², and more; On the other hand, obtaining historical and research data from different buildings is difficult and easily influenced by incomplete data and information bias¹³.

The third limitation is the limitation of research methods. For the selection of intervention levels in historical buildings, quantitative research methods are most commonly used to evaluate the facade, structure, materials, and decoration of the building's space¹⁴. However, the value and function of historical buildings cannot be quantified.

The second part of the literature review is about the concept of "minimal intervention" and intervention levels (Fig. 3). Burra Charter proposed the concept of "minimum impact". Article 7 states, "Compatible uses are those involving no change, changes which are substantially reversible, or changes which have a minimal impact on the culturally significant fabric"¹⁴. The emergence of "minimum intervention" coincides with technological and scientific advances in the 20th century. These advancements, realized in a philosophical approach to conservation, emerged as the technological means to carry them out were developed¹⁵. Regarding the vocabulary of different intervention levels, it is mainly mentioned in Burra Charter Conservation, Preservation, Restoration, Maintenance, Renewal, Reuse, Reconstruction, Adaptive reuse, Compatible use. Other related historical building intervention vocabulary includes Revitalization, Transformation¹⁶, Refurbishment, Regeneration¹⁷. Zhang and Dong⁶ summarized the minimum intervention level, but only used literature review methods, lacking a quantitative analysis framework and process for systematic research.

The third part of the literature review is about the evaluation factors that affect the selection of intervention levels. Mainly includes the following content: Protection regulations refer to the laws and regulations related to the historical building, including international, national, and local ones¹⁸. The protection level of historical buildings is divided into different protection levels and management standards based on their historical, artistic, scientific value, and preservation status¹⁹. The morphological and spatial characteristics of historical buildings are the most important basis for determining their reuse²⁰. In addition, the integrity of historical buildings includes two aspects: the integrity of the building and the integrity of the documents²¹. Historical buildings with high architectural integrity preserve more comprehensive historical information, while those with high document integrity can provide more comprehensive historical evolution information for their reuse²². Finally, functionality refers to whether the functions of historical buildings have changed during the process of reuse²³. When the original functions are no longer applicable to contemporary society, changes are made to their functions, such as transforming the original palace and sacrificial places into parks or museums. The above factors determine the selection of intervention types for historical buildings.

The fourth part of the literature review is about previous research methods. For the intervention level, there is a damaged information database that provides data support. For example, in the Yingxian Wooden Pagoda Protection Project, a three-dimensional database was established for more than 100000 components to quantitatively record parameters such as crack depth and decay area, and intervention levels were determined based on standardized thresholds²⁴. There is also the integration of computer simulation and experimental mechanics, such as the calibration of models for the brackets of the Yihe Hall in Shenyang Palace Museum through seismic test data, predicting the structural life under different intervention schemes²⁵. In addition, commonly used multi criteria decision analysis methods include TOPSIS ideal solution method, fuzzy comprehensive evaluation method, and cluster analysis method. TOPSIS can be calculated by weighting indicators to determine which approach is closer to the "minimum intervention" goal²⁶. The fuzzy comprehensive evaluation method quantifies fuzzy evaluations such as "good" and "average" through fuzzy membership functions, and then combines quantitative indicators for comprehensive decision-making²⁷. Cluster analysis can cluster historical buildings according to "Building type - Protection requirements" and establish a unified minimum intervention standard. Fuzzy comprehensive evaluation method is more suitable for situations where data is difficult to obtain or insufficient²⁸.

This study analyzes and summarizes existing research perspectives and elements. Therefore, the selection factors that affect the minimum intervention level of historical buildings are summarized into three target levels: Value assessment, usability assessment, and functional assessment. Value is a key factor in determining whether a historical building's functionality can be altered during its reuse, including protection level, artistic value, historical value, social value, and scientific value. Compared to value, usability assessment is the evaluation of the material carriers that carry value, including architectural features (layout, facade, structure, materials, decoration, and lighting), spatial features, and integrity. The final functional evaluation of historical buildings is an important factor in assessing whether the existing functions of historical buildings need to be changed²⁹.

Methods

Overview of Methodology

In order to achieve the research objectives, this study includes the following 5 steps:

Step 1: Based on literature search, establish a minimum intervention system framework for historical buildings (5 levels) (Table 2)

Step 2: Select the minimum intervention evaluation factors (3 target layers, 9 criterion layers, 29 factors) (Table 3)

Step 3: Select 14 heritage sites along the central axis of Beijing³⁰ and divide them into three categories: Sacrificial, Traffic-related, and Cultural landscape. (Table 4)

Step 4: Use Analytic Hierarchy Process to determine the weights of each element and indicator (Table 5). Evaluate the minimum intervention for 14 architectural heritage sites based on the scores obtained from a questionnaire survey. According to local laws and regulations, the investigation has been granted permission. 20 experts evaluated 29 factors with scores ranging from 1 to 9, forming a pairwise comparison matrix. 1-9 represents varying degrees of importance, ranging from poor to very good. These 20 experts are composed of academic experts from the departments of urban planning, urban history, architectural heritage, landscape, and cultural tourism. They are familiar with the historical and cultural heritage of Beijing and have been engaged in related work for more than 5 years.

This study complied with ethical research standards. Prior to participation, all experts were verbally informed of the following through online communication. The research aims to explore evaluation of the Protection of historical buildings along the Central Axis of Beijing. And Participation was voluntary, with the right to withdraw at any stage. No personal identifiers (e.g, names, affiliations) would be collected, and responses would be anonymized. Results may be published in academic venues without disclosing individual identities. Verbal consent was obtained from all

Table 3 | Minimum intervention level assessment factors for historical buildings

Target layer	Criterion layer	Indicator layer	Explanation	
value assessment	protection level	legality	Laws and regulations related to this historical building, including international, national, and local ones	
		protection level	Protection level of historical buildings	
	artistic value	uniqueness	The uniqueness of historical background	
		decorative	The aesthetic features and cultural symbols of historical buildings displayed through external art forms such as carving, painting, patterns, and components	
		spatial expressiveness	The functional imagery and emotional experience created by historical buildings through spatial organization techniques such as axes, levels, and opening closing relationships	
	historic value	continuity	As tangible witnesses of the changing times, historical buildings carry the historical context and social development information from their construction to the present day	
		educational	Historical architecture conveys historical knowledge, cultural traditions, and values through intuitive material forms, becoming a living textbook for future generations to understand and reflect on the past	
	social value	cultural heritage	Historical buildings serve as cultural carriers, continuing regional traditional customs, techniques, and spiritual connotations	
		economic	Historical buildings are transformed into economic value through cultural and tourism development, cultural creativity, and other forms, driving regional development	
		urban memory	As a collective emotional symbol, historical buildings embody citizens' sense of identity and belonging to the city	
	Scientific value	adaptability	The adaptability of historical buildings to the local natural and social environment	
		technical	Historical buildings contain the architectural technology of the time, showcasing the wisdom and engineering abilities of ancient people, and can provide reference and inspiration for modern architecture	
		diversity	Historical buildings have rich diversity in types, styles, regions, and other aspects	
	usability evaluation	visibility	layout	Refers to the visual order and rationality of the overall spatial planning and functional zoning of a building, reflecting the recognizability and logical use of spatial organization
			facade	The external appearance of a building, consisting of walls, doors, windows, eaves, etc., reflecting the architectural style, historical features, and visual coordination with the surrounding environment
structure			Refers to the visible form of the load-bearing system of a building (such as beams, columns, walls, roofs, etc.), demonstrating the historical significance of construction techniques and the intuitive expression of mechanical logic	
material			Refers to the visible texture, color, and weathering state of materials such as bricks, wood, metal, etc. used on the inner and outer surfaces of a building, conveying the age information and technological characteristics of the building	
decoration			Refers to the visible artistic treatment of building components (such as carving, painting, patterns, etc.), reflecting historical and cultural connotations, aesthetic orientation, and craftsmanship level	
night lighting			Refers to the nighttime visual presentation of building appearance and details through lighting design, emphasizing the recognizability of historical features at night and the creation of environmental atmosphere	
spatial features		types of public spaces	The types of spaces available for public use inside and outside historical buildings (such as squares, courtyards, corridors, etc.) reflect the diversity of spatial functions and the adaptability of public participation	
		spatial recognition	The visual recognizability of various functional spaces in historical buildings (such as entrances, exhibition halls, traffic flow lines, etc.) presented through form, signage, or historical elements, ensuring that users can quickly understand the spatial attributes and orientation	
		spatial quality	The physical and visual effects of historical architectural spaces, such as lighting, ventilation, color matching, scale ratios, etc., need to balance the protection of historical features with the comfort of modern usage needs	
		integration of old and new spaces	Refers to the degree of coordination and unity in visual elements such as material, form, and scale between the original space of historical buildings and newly built/renovated spaces, reflecting the continuity of historical context and the compatibility of contemporary functions	
integrity		complete historical architecture	The degree of integrity of the architectural entity (such as structure, components, decoration, site, etc.) of a historical building, ensuring that the core historical elements are not missing, tampered with, or excessively damaged	
		complete literature	The completeness and accuracy of archives, drawings, images, written records, and other documentary materials related to historical buildings, which should comprehensively and truthfully reflect the historical evolution, construction techniques, and cultural value of the buildings	
functional evaluation		functionality	diverse functions	The richness of functional types that historical buildings can carry in the process of reuse (such as cultural exhibitions, commercial services, office and residential areas, etc.), while taking into account the adaptability of historical value protection and diverse social needs
			flexible space	Refers to the dynamic adaptability of the internal space of a building to different usage scenarios (such as exhibitions, conferences, retail, etc.) through adjustable layout, modular design, or multifunctional furniture
			modern facilities	Refers to the organic integration of historical style and contemporary usage needs by incorporating modern technologies (such as HVAC, fire protection, intelligent systems) and design language while preserving the core elements of historical buildings
			barrier-free design	Refers to the elimination of physical barriers (such as ramps, elevators, braille signage, etc.) to ensure the convenience and safety of historical buildings for different groups of people (such as disabled and elderly), in line with modern inclusive design principles

Table 4 | Information on case studies








Type	Historical buildings	Year of construction	Intervention year (becoming a new function)	Original function	New function	Picture
Sacrificial	the Imperial Palace	1406-1420	1925	Royal palaces of the Ming and Qing dynasties	museum	
	the Imperial Ancestral Temple	1420	1924	The places where emperors of the Ming and Qing dynasties worshipped their ancestors	The Labor People's Cultural Palace combines historical building protection, cultural event hosting, and public leisure facilities	
	Altar of Land and Grain	1420	1914	The places where emperors of the Ming and Qing dynasties worshipped the God of Land and the God of Five Grains	Zhongshan Park has the functions of protecting historical buildings, providing leisure and recreation for citizens, and hosting cultural activities	
	Temple of Heaven	1420	1918	The place where emperors of the Ming and Qing dynasties worshipped the heavens and prayed for a bountiful harvest of crops	The Temple of Heaven Park combines the functions of historical and cultural heritage protection, citizen leisure and recreation, and science popularization education	
	Xiannong Altar	1420	1915	The place where emperors of the Ming and Qing dynasties worshipped the god of agriculture and held the ceremony of cultivating crops	The Beijing Museum of Ancient Architecture focuses on protecting historical buildings, showcasing ancient Chinese architectural art, and organizing related cultural activities	
Traffic-related	Wanning Bridge	1285	1925	Bridge, responsible for connecting the north and south transportation of Beijing and ensuring the transportation of goods by canal	A historical cultural relic protection unit that serves as a transportation hub (partially), historical landscape display, and central axis cultural heritage marker	

Table 4 (continued) | Information on case studies

Type	Historical buildings	Year of construction	Intervention year (becoming a new function)	Original function	New function	Picture
	Duan Gate	1420	1925	The prelude portal of the Forbidden City during the Ming and Qing dynasties, responsible for guarding, buffering etiquette, and storing imperial ceremonial equipment	As an integral part of the Palace Museum, it serves as both a historical building protection, cultural relic display (in some areas), and a tourist gathering channel	
	Tiananmen	1420	1949	The main entrance of the imperial city during the Ming and Qing dynasties	Important historical relics and national symbols, with the functions of protecting historical buildings, hosting major celebration events, and attracting tourists for sightseeing	
	Waijinshui Bridge	1420	1949	The ceremonial bridge in front of the imperial city during the Ming and Qing dynasties was only for the emperor, nobles, and ministers to pass through according to their ranks, reflecting the order of the royal ritual system	Historical landscape display, cultural relic protection, and functions for tourists to visit	
Cultural landscape	Bell tower and drum tower	1420	1957	The Time Reporting Center of Beijing during the Ming and Qing Dynasties	The Bell and Drum Tower Museum is responsible for the protection of historical buildings, the display of ancient timekeeping culture, and providing visitors with access to the museum	
	Jingshan Park	1424	1928	During the Ming and Qing dynasties, it was a royal garden that served the functions of protecting the city, providing scenic views, and offering sacrifices	National level cultural relics protection units and urban parks undertake the functions of historical landscape protection, citizen leisure and recreation, cultural exhibition, and tourist visits	
	Tiananmen Square and its architectural complex	1420	1949	The ceremonial square in front of the royal forbidden area during the Ming and Qing dynasties	National important celebrations and gathering places, as well as historical and cultural landmarks and public spaces for domestic and foreign tourists to visit, carry national symbols and commemorative significance	
	Zhengyang Gate	1906	1949	During the Ming and Qing dynasties, it served as the main entrance of Beijing's inner city, with both urban defense and access control functions	Museums (showcasing the history of Beijing's urban changes, etc.) are important landmarks and cultural tourist attractions along the central axis of Beijing	
	Yongding Gate	1553	2004	During the Ming and Qing dynasties, it served as the main entrance to the outer city of Beijing, responsible for urban defense and access management functions, and was also a gateway node for southern materials to enter the capital	The historical landmark at the southern starting point of Beijing's central axis serves as a showcase of the axis's history and traditional architectural techniques, while also serving as a place for citizens to relax and experience culture	

participants, consistent with the non-sensitive nature of the study and the expert participant group.

Step 5: The comprehensive evaluation of 14 heritage sites along the central axis of Beijing was conducted using the fuzzy evaluation method, and the score results verified that the protection intervention methods for his-

torical buildings along the central axis of Beijing were all minimal interventions. Multiply the obtained data by the weight of the indicator and convert it into a percentile system to obtain the level and score of each building intervention. (Tables 6, 7)

Step 6: Formulate the minimum intervention selection strategy and develop the minimum intervention measures. (Table 11)

In response to the limitations of the research perspectives, subjects, and methods mentioned in the literature review above, this study has made the following improvements:

In terms of research perspective, this study chooses the historical buildings of the Beijing central axis (including different intervention levels) and constructs a minimum intervention evaluation system for historical buildings with value evaluation, usability evaluation, and functional evaluation as the target layers. This fills the gap in previous research that only focused on a single historical building and a particular intervention method. In the research direction, 14 historical buildings along the central axis of Beijing were selected to fill the gap in comparative analysis of different intervention methods for different historical buildings under the same historical and cultural background. And divide these 14 historical buildings into three types: Sacrificial, Traffic-related, and Cultural landscape. Excessive cases may lead to complexity in data analysis, making it difficult for research to delve into the uniqueness and details of each building type. 14 cases can maintain the depth and concentration of research while maintaining representativeness.

Table 5 | The standard comparison matrix

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

Table 6 | RI values corresponding to the order of comparison matrix(n)

n	1	2	3	4	5	6	7	8	9
RI Value	0	0	0.52	0.89	1.12	1.26	1.36	1.41	1.45

Table 7 | Indicator weight

Target	Weight	Criterion	Weight	Indicator	Weight	Comprehensive Weight		
A1	0.3	B11	0.3128	C111	0.25	0.0235		
				C112	0.75	0.0704		
				C121	0.1823	0.0074		
		B12	0.1349	C122	0.1008	0.0041		
				C123	0.7168	0.0290		
				C131	0.6667	0.0626		
		B13	0.3128	C132	0.3333	0.0313		
				C141	0.6370	0.0229		
		B14	0.1198	C142	0.1047	0.0038		
				C143	0.2583	0.0093		
				C151	0.3196	0.0115		
		B15	0.1196	C152	0.5584	0.0200		
				C153	0.1220	0.0044		
				C211	0.2738	0.0172		
		A2	0.2	B21	0.3090	C212	0.2738	0.0172
C213	0.1536					0.0095		
C214	0.1536					0.0095		
C215	0.0890					0.0055		
C216	0.0563					0.0035		
C221	0.2544					0.0296		
B22	0.5816			C222	0.3229	0.0376		
				C223	0.3814	0.0444		
				C224	0.0413	0.0048		
				C231	0.6	0.0131		
B23	0.1095			C232	0.4	0.0088		
				C311	0.5683	0.2526		
A3	0.5			B31	1	C312	0.2659	0.1182
						C313	0.1191	0.0529
						C314	0.0467	0.0208

In terms of research methods, determining the “minimum intervention level” in the protection of historical buildings is a typical multi-criteria decision-making problem, involving the ambiguity of value judgments, the diversity of evaluation factors, and the integration of expert experience. This study used the AHP-FCE method for comprehensive calculations. Firstly, the minimum intervention decision is a multifactorial problem involving various aspects such as history, art, scientific value, structure, materials, and technical feasibility. The structured decomposition ability of AHP is the foundation. Secondly, predictions such as value assessment and status assessment are difficult to quantify accurately, and there are a large number of vague language descriptions. FCE is a powerful tool for dealing with this ambiguity. Therefore, the multi-level and multi angle comprehensive evaluation information provided by AHP-FCE helps decision-makers to have a more comprehensive understanding of the potential impacts of different intervention levels. In summary, AHP provides a systematic framework for scientifically determining the weights of complex evaluation systems, while FCE provides an effective tool for dealing with the inherent ambiguity of evaluation information. Combining the two methods for specific evaluation factors and intervention level settings in the case of the central axis will fully demonstrate the applicability and research value of this method.

Case information

The “Beijing Central Axis” runs through the north and south of the old city of Beijing. It was first built in the 13th century and formed in the 16th century³¹. After continuous evolution and development, it has become the longest urban axis in the world, with a total length of 7.8 kilometers today. On July 27, 2024, Beijing Central Axis successfully applied for World Heritage at the 46th UNESCO World Heritage Conference held in New Delhi, India, and was officially included in the The World Heritage List. The 14 heritage sites along the central axis of Beijing are important historical and cultural relics. (Table 4)

Analytic hierarchy process (AHP)

The weights of the indicators were determined by the method of the analytic hierarchy process and represent the different effects on the intervention level of historical buildings along the central axis of Beijing. The weight vector *W* consists of the 29 indicator weights and *w_i* represents the weight of the indicator *i*, and $\sum_{i=1}^{29} w_i = 1$, as shown in Eq. 1.

$$W = [w_1, w_2, \dots, w_{29}] \tag{1}$$

The weight *w_i* is determined by the analytic hierarchy process. First, the pairwise comparison matrices are constructed by 20 experts from academic professionals in urban planning, history, architectural history, landscape, and cultural tourism department using a scale from 1 to 9 to show the relative importance of each indicator, from the least important to the most important. The standard comparison matrix is shown in Table 5, where $B_{ij} = 1/B_{ji}$, $B_{ii} = 1$.

Second, the principal eigenvalue is calculated for each pairwise comparison matrix, and the corresponding eigenvector is calculated to show the relative weights among the indicators. Then, the consistency index *CI* is calculated using the Eq.(2). Finally, we checked the consistency ratio *CR* by comparing it with the random consistency index *RI* using the Eq.(3). If $CR < 0.1$, the consistency of the comparison matrix is considered acceptable; otherwise, the comparison matrix needs to be adjusted. The *RI* value is a crucial criterion for testing the consistency of the comparison matrix and can be obtained from Table 6 of the average random consistency index.

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{2}$$

$$CR = \frac{CI}{RI} \tag{3}$$

After the comparative analysis and calculation, the weights of target A, criterion B and indicator C were obtained as shown in Table 7. The comprehensive weight *w_i* was calculated as follows:

$$\begin{aligned} &\text{Comprehensive weight } w_i \text{ of indicator } i \\ &= (\text{weight of indicator } i) \\ &\times (\text{weight of criterion B attached to indicator } i) \\ &\times (\text{weight of target C attached to indicator } i) \end{aligned} \tag{4}$$

According to Eq. (4), the weight vector *W* was calculated as follows:

$$\begin{aligned} W = [&0.0235, 0.0704, 0.0074, 0.0041, 0.0290, \\ &0.0626, 0.0313, 0.0229, 0.0038, 0.0093, \\ &0.0115, 0.0200, 0.0044, 0.0172, 0.0172, \\ &0.0095, 0.0095, 0.0055, 0.0035, 0.0296, \\ &0.0376, 0.0444, 0.0048, 0.0131, 0.0088, \\ &0.2526, 0.1182, 0.0529, 0.0208] \end{aligned} \tag{5}$$

Fuzzy comprehensive evaluation method

Fuzzy comprehensive evaluation method is a comprehensive evaluation method based on fuzzy mathematics, and transforms qualitative evaluation into quantitative evaluation based on the membership theory of fuzzy mathematics. The method has the characteristics of clear results and strong systematicity, which can effectively solve fuzzy and difficult to quantify problems, and is suitable for solving various non deterministic problems. The application of fuzzy comprehensive evaluation method follows the following steps. First, it should determine the evaluation description set. The evaluation description set *V* is used with 4 levels from excellent to poor for each indicator *i*.

$$V = \{\text{Excellent, Good, Moderate, Poor}\} \tag{6}$$

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

$$R^k = \begin{bmatrix} r_{1,1}^k & r_{1,2}^k & r_{1,3}^k & r_{1,4}^k \\ r_{2,1}^k & r_{2,2}^k & r_{2,3}^k & r_{2,4}^k \\ \vdots & \vdots & \vdots & \vdots \\ r_{29,1}^k & r_{29,2}^k & r_{29,3}^k & r_{29,4}^k \end{bmatrix} \tag{7}$$

Third, the fuzzy comprehensive evaluation vector should be determined. 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*.

$$\begin{aligned} C^k = W \cdot R^k &= [w_1, w_2, \dots, w_{29}] \cdot \begin{bmatrix} r_{1,1}^k & r_{1,2}^k & r_{1,3}^k & r_{1,4}^k \\ r_{2,1}^k & r_{2,2}^k & r_{2,3}^k & r_{2,4}^k \\ \vdots & \vdots & \vdots & \vdots \\ r_{29,1}^k & r_{29,2}^k & r_{29,3}^k & r_{29,4}^k \end{bmatrix} \\ &= [c_1^k, c_2^k, c_3^k, c_4^k] \end{aligned} \tag{8}$$

Finally, the minimum intervention level was measured through the comprehensive evaluation score. The comprehensive evaluation scores are expressed in the percentile system. The score vector P corresponding to the evaluation description set is expressed as $P = [93, 77, 62, 47, 20]^T$, and the intervention score is expressed as follows:

$$S = C^k \cdot P \tag{9}$$

Results

Comprehensive evaluation results

This study is based on the constructed framework for evaluating the minimum intervention level of historical buildings. The AHP is used to determine the weights of each evaluation indicator, and the FCE is combined to evaluate the intervention level of 14 historical buildings along the central axis of Beijing. The evaluation grades are shown in Table 8 and the evaluation results are shown in Table 9.

From the evaluation results, the intervention levels of 14 historical buildings cover four levels: B, C, D, and E (Table 9), with the specific distribution as follows:

Repair: (B, 84-70 points): There are 2 buildings in this level, both belonging to the Traffic-related category, namely Wanning Bridge (73 points) and Waijinshui Bridge (75 points). This indicates that the current condition of these two buildings requires a certain degree of restoration intervention to maintain their historical style and functional use.

Renewal: (C, 69-55 points): Only one building belongs to this level, namely Tiananmen Square and the architectural complex in the cultural landscape category (65 points). This type of building requires renovation interventions to better adapt to modern usage needs while preserving historical features.

Reuse: (D, 54-40 points): This level has the highest number of buildings, with a total of 10, distributed in the categories of Sacrificial, Traffic-

related, and Cultural landscapes. Among them, the Forbidden City (51 points), the Temple of Heaven (50 points), the Temple of State (47 points), the Temple of Heaven (50 points), and the Temple of Agriculture (48 points) belong to the Sacrificial category; Duan Gate (46 points) and Tiananmen Square (53 points) belong to the category of Traffic-related; Bell tower and drum tower (54 points), Jingshan Park (51 points), and Zhengyang Gate (48 points) in the cultural landscape category all belong to this level. This means that in the process of reuse, these buildings need to change their functions in order to achieve a balance between protection and utilization.

New Design: (E, 40-0 points): Only Yongding Gate in the cultural landscape category (37 points) belongs to this level, indicating that it requires significant intervention such as reconstruction.

Overall, the intervention levels of 14 historical buildings along the Beijing central axis are distributed in a ratio of 2:1:10:1 (B: C: D: E), and all intervention methods of the buildings comply with the principle of minimum intervention, verifying the applicability of the method for selecting the minimum intervention level for historical buildings constructed in this study.

Criteria level evaluation results

The common feature of the value evaluation criteria layer (B11-B15) (Table 10) is that all buildings have a high “protection level (B11)” score (3.76-8.22), with only Yongding Gate (3.76) receiving a low score due to its low protection level; The overall score for “artistic value (B12)” is relatively low (0.72-3.40), with Yongding Gate having the lowest score (0.72); The “Historical Value (B13)” score is above average (5.63-7.75), with Waijinshui Bridge and Wanning Bridge (both 7.75) having the highest scores, and Yongding Gate (5.63) having the lowest. Differences in different categories: Sacrificial category: “Protection level (B11)” is 8.22 (highest level), while “Social value (B14)” and “Scientific value (B15)” have stable ratings (2.03-2.77). Traffic-related category: Tiananmen Square and Waijinshui Bridge have a “protection level (B11)” of 8.22 and “artistic value (B12)” of 3.40. Tiananmen Square has the highest “historical value (B13)” of 7.75 (the highest within the category). Cultural landscape category: Yongding Gate has the lowest multiple indicators (B11 = 3.76, B12 = 0.72) among all buildings; Tiananmen Square and its architectural complex have the highest social value (B14) of 3.01 and scientific value (B15) of 2.57 within their respective categories.

The characteristics of the usability evaluation criteria layer (B21-B23) (Table 11) are: all buildings have the lowest “integrity (B23)” score (0.66-1.81), and Yongding Gate (0.66) has the lowest score; The visibility score (B21) is moderate (4.18-5.24), with Wanning Bridge (5.21) and Waijinshui

Table 8 | Evaluation grades

Score	Intervention level	Intervention Actions	Grades
100-85	Maintenance	Preservation	A
84-70	Repair	Renovation	B
69-55	Renewal	Revitalization	C
54-40	Reuse	Adaptive reuse Compatible use	D
39-0	New Design	Reconstruction Regeneration	E

Table 9 | Evaluation results

Type	Number	Historical buildings	Intervention level	AHB level	Score range	Score
Sacrificial	1	the Imperial Palace	Reuse	D	39-20	51
	2	the Imperial Ancestral Temple	Reuse	D	39-20	47
	3	Altar of Land and Grain	Reuse	D	39-20	48
	4	Temple of Heaven	Reuse	D	39-20	50
	5	Xiannong Altar	Reuse	D	39-20	44
Traffic-related	6	Wanning Bridge	Repair	B	79-60	73
	7	Duan Gate	Reuse	D	39-20	46
	8	Tiananmen	Reuse	D	39-20	53
	9	Waijinshui Bridge	Repair	B	79-60	75
Cultural landscape	10	Bell tower and drum tower	Reuse	D	39-20	54
	11	Jingshan Park	Reuse	D	39-20	51
	12	Tiananmen Square and its architectural complex	Renewal	C	59-40	65
	13	Zhengyang Gate	Reuse	D	39-20	48
	14	Yongding Gate	New Design	E	19-0	37

Table 10 | Criteria level evaluation results

Type	Historical buildings	B11	B12	B13	B14	B15
Sacrificial	the Imperial Palace	8.22	3.11	7.39	2.68	2.75
	the Imperial Ancestral Temple	8.22	2.76	6.81	2.67	2.40
	Altar of Land and Grain	8.22	2.98	6.83	2.63	2.33
	Temple of Heaven	8.22	3.04	7.24	2.51	2.77
	Xiannong Altar	8.22	2.66	6.89	2.49	2.03
Traffic-related	Wanning Bridge	8.22	2.85	7.59	3.01	2.84
	Duan Gate	7.51	2.74	6.73	2.59	2.12
	Tiananmen	8.22	3.40	7.28	2.75	2.28
	Waijinshui Bridge	7.75	3.19	7.75	2.99	2.99
Cultural landscape	Bell tower and drum tower	8.22	3.33	7.28	2.80	2.31
	Jingshan Park	8.22	3.14	7.04	2.75	2.75
	Tiananmen Square and its architectural complex	7.98	3.40	7.59	3.01	2.57
	Zhengyang Gate	8.22	2.74	6.57	2.69	2.63
	Yongding Gate	3.76	0.72	5.63	2.66	2.28

Table 11 | Criteria level evaluation results

Type	Historical buildings	B21	B22	B23
Sacrificial	the Imperial Palace	5.03	6.79	1.75
	the Imperial Ancestral Temple	4.94	6.22	1.70
	Altar of Land and Grain	4.67	6.84	1.71
	Temple of Heaven	5.05	6.67	1.75
	Xiannong Altar	4.59	5.33	1.64
Traffic-related	Wanning Bridge	5.21	9.36	1.81
	Duan Gate	4.59	6.46	1.64
	Tiananmen	4.79	7.35	1.61
	Waijinshui Bridge	5.24	9.73	1.72
Cultural landscape	Bell tower and drum tower	4.68	7.62	1.62
	Jingshan Park	5.07	6.98	1.75
	Tiananmen Square and its architectural complex	5.01	8.79	1.81
	Zhengyang Gate	4.18	6.69	1.65
	Yongding Gate	4.41	5.91	0.66

Bridge (5.24) being the highest in the Traffic-related category. Differences in Different Categories: Sacrificial Category: “Spatial Features (B22)” has a stable rating (5.33-6.84), while the Temple of Heaven (6.67) and the Altar of Land and Grain (6.84) have higher ratings; The “integrity (B23)” ranges from 1.64 to 1.75, with no significant difference. Traffic-related category: “Spatial features (B22)” Wanning Bridge (9.36) and Waijinshui Bridge (9.73) are much higher than other buildings, and are the highest values among all buildings; The visibility (B21) of the Waijinshui Bridge (5.24) is the highest. Cultural landscape category: Tiananmen Square and architectural complex have the highest visibility (B21) 5.01 and spatial features (B22) 8.79 within the category; The integrity (B23) of Yongding Gate is 0.66, which is the lowest among all buildings.

Significant differences in functional evaluation criteria layer (C31) (Table 12): The scoring of functional evaluation (C31) is polarized significantly, with Wanning Bridge (32.21) and Waijinshui Bridge (33.50) in the Traffic-related category receiving the highest scores, far exceeding other buildings; The Sacrificial Category (10.67-13.38) and Cultural Landscape Category (9.54-24.94) have lower scores, with Yongding Gate (9.54) having

Table 12 | Criteria level evaluation results

Type	Historical buildings	C31
Sacrificial	the Imperial Palace	13.38
	the Imperial Ancestral Temple	11.30
	Altar of Land and Grain	11.93
	Temple of Heaven	12.80
	Xiannong Altar	10.67
Traffic-related	Wanning Bridge	32.21
	Duan Gate	11.59
	Tiananmen	15.38
	Waijinshui Bridge	33.50
Cultural landscape	Bell tower and drum tower	16.50
	Jingshan Park	14.64
	Tiananmen Square and its architectural complex	24.94
	Zhengyang Gate	12.80
	Yongding Gate	9.54

the lowest score. Category rule: The Traffic-related category adapts to modern transportation functions as needed, and its “functionality” score is significantly higher than that of the sacrificial category and the cultural landscape category.

Intervention measures

Based on the intervention level evaluation results of 14 historical buildings, combined with the principle of minimum intervention and the value, usability, and functional indicators in the evaluation framework, differentiated intervention measures were developed for different intervention levels, as follows:

Maintenance (A, 100-85 points): This level is applicable to buildings with excellent preservation status, outstanding historical value, and functional integrity. The intervention measures are centered on preventive protection, including visibility maintenance: regular inspection of the integrity of building layout, facade, structure, and materials, focusing on monitoring the stability of decorative details and night lighting systems to ensure the visual recognizability of historical features (such as the clarity of carved patterns and the restoration of building contours by lighting). Availability maintenance: Verify the adaptability and spatial quality of public space types (such as lighting and ventilation), ensure the normal operation of modern facilities (such as fire protection systems), while preserving the continuity of original functions. This type of measure emphasizes “Not changing the current status and function of the building” and only delaying aging through daily maintenance, which meets the core requirements of “integrity of the building” and “continuity of historical value” in the evaluation framework (Table 13).

Repair (B, 84-70 points): For buildings such as Wanning Bridge (73 points) and Waijinshui Bridge (75 points) that require partial repair, the intervention measures are based on the principle of protective repair, including: visibility repair: replacing damaged structural components (such as the stone carved railings of Waijinshui Bridge), repairing weathered materials (such as the brick and stone surfaces of Wanning Bridge), and optimizing night lighting to highlight historical features without changing the original style and shape of the building. The repair material must meet the “compatibility” requirements and maintain coordination with the texture and color of the original material. Usability repair: On the basis of preserving historical functions, integrate modern facilities (such as monitoring systems and anti-slip paving) to enhance spatial safety and convenience, while avoiding the disruption of the coordination between “spatial recognition” and “integration of old and new spaces”. This measure balances the protection of “artistic value decorative” with modern usage needs, and meets the dual requirements of functionality and safety for transportation hub buildings.

Table 13 | Intervention level and measures

Intervention level	Intervention measures
Maintenance	Regular inspection and cleaning 1. Visibility inspection: Check the safety of the indoor and outdoor structure, materials, and lighting of the building 2. Usability check: whether the space is used reasonably and whether modern facilities are operating normally
Repair	Maintenance to maintain the original style of the building 1. Visibility maintenance: Replace materials, structures, or lighting equipment without damaging the style and appearance of the building's interior and exterior 2. Usability maintenance: Install modern facilities such as air conditioning, cameras, etc. without damaging the style and appearance of the building's interior and exterior
Renewal	Update to change some functions 1. Visibility update: Unified building facade style, materials, and structure without changing the overall layout 2. Usability update: Without changing the overall layout, functional parts will be changed, space will be utilized reasonably, modern facilities will be used, and accessible design will be added
Reuse	Change the reuse of all functions 1. Reuse of visibility: The external facade style remains unchanged, and new technologies are integrated into materials, structures, and surfaces. 2. Usability Reuse: Injecting new functions into the interior space of the building, modernizing the use of space, integrating new technologies and accessible design of the times
New Design	Rebuilding on the original site 1. Visibility reconstruction: Layout and elevation are reconstructed based on historical information, while materials, structures, and lighting are selected according to contemporary standards 2. Usability reconstruction: injecting new functions into the interior space of the building, modernizing the use of space, integrating new technologies of the times and accessible design

Renewal (C, 69-55 points): This intervention level applies to Tiananmen Square and the building complex (65 points), with a focus on functional updates, including: visibility updates: while maintaining the overall layout and historical style, unifying the building facade style and materials (such as the treatment of eaves around the square), repairing visible parts of damaged structures (such as columns and steps), and ensuring visual coordination with the surrounding environment. Availability update: moderately adjust some space functions (such as adding a tourist service center), optimize the type of public space (such as expanding the area of the distribution square), integrate barrier free design (such as ramps, tactile paving), and improve the use experience through intelligent systems (such as navigation screens). This type of measure not only satisfies the “social value economy” (optimization of cultural and tourism functions), but also ensures that the update plan conforms to historical records through “literature integrity” verification.

Reuse (D, 54-40 points): This intervention level is applicable to 10 buildings, including the Forbidden City (51 points) and the Temple of Heaven (50 points). The intervention measures focus on reuse, including: visibility reuse: strictly preserving the historical features of the building's exterior facade and decoration (such as the glazed tiles of the Hall of Supreme Harmony in the Forbidden City and the wooden patterns of the Hall of Prayer for Good Harvests in the Temple of Heaven), but integrating modern technology into the internal structure and materials (such as moisture-proof and anti-corrosion treatment, concealed support components) to avoid visual abruptness. Usability Reuse: Functional reconstruction of the interior space of the building (such as converting the Temple of Heaven into a cultural exhibition hall, adding a folk experience area to the Bell and Drum Tower), enhancing “spatial flexibility” through flexible layout and modular design, integrating modern facilities such as HVAC and fire protection, and improving barrier free access to adapt to diverse usage scenarios. This measure maximizes the preservation of “historical value continuity” and “scientific value technicality”, while achieving cultural inheritance through functional transformation.

New design (E, 39-0 points): This intervention level is applicable to Yongding Gate (37 points), and the intervention measures mainly focus on reconstruction, including: visibility reconstruction: restoring the building layout and facade form based on archival documents (such as Qing Dynasty drawings), selecting materials and structures that balance historical authenticity and contemporary standards (such as using antique bricks and reinforced concrete concealed frames), and lighting design that highlights the building outline and iconic components (such as city tower plaques). Usability reconstruction: Inject new functions (such as the Central Axis

Cultural Museum), adopt modern layout in the internal space (such as exhibition halls and lecture halls), integrate intelligent management systems and accessible facilities, and improve the user experience through “space quality” optimization (such as natural lighting and acoustic treatment). The reconstruction process must strictly follow the verification results of “literature integrity” to ensure the accurate restoration of core historical information.

In summary, all types of intervention measures are based on the 29 factors of the evaluation framework, achieving a balance between historical value protection and modern functional needs under the principle of “minimum intervention”, and verifying the scientificity and applicability of this method³².

Discussion

The method proposed in this study for selecting the minimum intervention level of historical buildings provides a new approach for the field of historical building protection. Its core lies in transforming the abstract principle of “minimum intervention” into actionable quantitative tools through the construction of a system framework and evaluation system, which is in line with the international trend of heritage conservation shifting from empiricism to empiricism³³.

From a theoretical perspective, the 5 intervention levels and evaluation framework established in this study, which includes 3 target layers, 9 criterion layers, and 29 factors, enrich the evaluation dimensions of historical building protection. This framework considers both the physical properties of the building itself, such as structure and materials, as well as its cultural value and social function, responding to Labadi’s discourse on the diversity of heritage values³⁴. At the same time, the 14 historical buildings along the central axis of Beijing were classified into Sacrificial, Traffic-related, and Cultural landscape categories for research, reflecting the emphasis on functional types of buildings and consistent with the heritage classification and protection concept³⁵. Heritage value is dynamically constructed through functionality and cultural context.

In terms of method application, the combination of AHP and FCE effectively solves the problem of multiple factors and ambiguity in the selection of intervention levels for historical buildings. The AHP can scientifically assign weights to 29 evaluation factors, reducing subjective arbitrariness, which is consistent with original intention when proposing this method³⁶; The fuzzy evaluation rule can effectively handle the uncertainty in the evaluation process and improve the reliability of the results³⁷. The collaborative use of the two methods provides strong technical support for determining the minimum

intervention level of historical buildings, which is consistent with the composite method approach adopted by Liu et al. in similar studies³⁸.

The research results show that 14 historical buildings along the central axis of Beijing are divided into four categories in a ratio of 2:1:10:1, and all use minimal intervention methods. The conclusion not only verifies the consistency between the protection practice of historical buildings along the Beijing central axis and the principle of “minimum intervention”, but also provides a scientific basis for the subsequent reuse and sustainable development of historical buildings in the region. This is consistent with the research conclusion of Zhang and Han on the protection of historical buildings in Beijing, that is, reasonable intervention level classification is the key to achieving sustainable use of historical buildings³⁹.

Regarding the extension of methods. Localized adjustments can be made to the 29 evaluation factors proposed in this study. For example, strengthening the weight of “material compatibility” and supplementing “moisture-proof and anti-corrosion” factors for wooden structure buildings in water towns, as well as adding “weathering degree assessment” for brick and stone buildings in arid areas, reflect respect for the characteristics of buildings in different regions, which is in line with Pickard’s concept of regional heritage protection⁴⁰. At the same time, the strategy of piloting in areas with commonalities with Beijing’s central axis architecture and gradually promoting it to areas with significant cultural differences can help reduce the risk of method application, which is in line with Keitsch’s progressive concept of promoting heritage conservation methods⁴¹.

Although this study has achieved certain results, there are still some limitations. Firstly, the selection of evaluation factors may not be comprehensive enough. Although the 29 evaluation factors were obtained through literature analysis, the protection of historical buildings is influenced by multiple complex factors, and there may be some special factors that have not been included in different regions and types of historical buildings. For example, for some historical buildings with significant religious significance, the impact of religious activities on the building may be an important evaluation factor, but this study did not explicitly include it. Future research can refer to Hays’s study on the relationship between culture and architecture to further expand the scope of evaluation factors⁴².

Secondly, the construction of the judgment matrix in the AHP relies on expert opinions and may have a certain degree of subjectivity. Although experienced experts were selected as much as possible during the research process, there are differences in their knowledge backgrounds and cognitive levels, which may lead to bias in weight allocation results. This is consistent with the limitations of the Analytic Hierarchy Process in subjective judgment pointed out by Bernasconi et al.⁴³. Although the AHP-FCE method used in this study provides a systematic analysis framework for the decision-making of the minimum intervention level for historical buildings on the central axis, lacking completely objective quantitative indicators to support it, and without external measured data, the research conclusion precisely verifies that the intervention methods for historical buildings on the central axis in Beijing are all minimal interventions. This limitation stems from the particularity of intervention decision-making in historical buildings: core evaluation dimensions such as historical value and cultural significance are difficult to quantify through a single objective data, and need to be combined with interdisciplinary experts’ comprehensive analysis of the building’s intrinsic characteristics, historical context, and protection and inheritance needs. However, there is currently no universally applicable objective quantitative standard in academic research. To enhance the credibility and reproducibility of the conclusions, subsequent research can be improved through the following paths: firstly, expanding the scope of expert consultation to include diverse subjects such as technical personnel in building protection engineering, researchers in historical geography, and practitioners in cultural relic management; The second is to introduce objective data of the built environment (such as building structure health monitoring data and quantitative analysis results of historical literature) as a supplement, and construct a mixed evaluation system of “subjective judgment+objective data”; The third is to select historical building cases from different regions and types for cross scenario verification, extract the applicable boundaries and correction

parameters of the model. The value of this study lies in establishing an analytical logic that balances multidimensional evaluation indicators with fuzzy decision-making needs, and its core conclusions can still provide a reference framework for similar historical building protection decisions.

Thirdly, the determination of membership function in the FCE has some experience. The shape and parameter settings of the membership function directly affect the accuracy of the evaluation results, and currently there is no unified standard for the membership function of historical building intervention level evaluation. In the future, more practical cases can be combined to optimize the determination of membership functions through machine learning and other methods, in order to improve the objectivity of evaluation⁴⁴.

Fourthly, although the 14 historical buildings along the central axis of Beijing are typical cases officially published, which can better reflect the core characteristics of historical buildings in the region, the samples only cover architectural groups within a single cultural context. And most buildings have maintained their foundations through regular maintenance, and the core contradiction of their intervention decisions is more focused on the balance between historical value protection and reuse, rather than emergency repair needs. Subsequent research can separately add a first level indicator of “damage degree” to refine quantitative standards for component diseases, structural degradation, etc; The conclusion of this study still applies to intervention decisions for similar “low-risk” historical buildings, and its weight allocation logic can provide reference for indicator design in specific protection scenarios.

The evaluation framework constructed in this study highlights the reuse orientation of historical buildings in terms of value, usability, and functional dimensions. However, it should be clarified that the “protection and restoration” and “reuse” of historical buildings are not in opposition, but rather an organic unity in the context of protection and inheritance - reuse is one of the core goals of protection and restoration, and scientific protection and restoration measures are a prerequisite for achieving sustainable reuse. The core logic of framework design is based on the principle of “protection first, rescue first, rational utilization, and strengthened management” in the “Guidelines for the Protection of Chinese Cultural Relics and Monuments”. The consideration of historical information integrity and architectural authenticity in the value evaluation dimension, as well as the setting of indicators for structural safety and stability and style continuity in usability evaluation, are essentially to delineate the core boundaries of protection and restoration measures: the decision of the lowest intervention level needs to be based on meeting the core requirements of protection and restoration, and then achieve the goal of rational utilization through functional and usability evaluation. For example, the weight assignment of historical architectural features directly determines the core components and shapes that need to be preserved during the intervention process, indirectly guiding the application of protection technologies such as repair material selection and structural reinforcement methods; And the evaluation of functionality and usability avoids the loss of building vitality caused by “protecting for the sake of protection”, achieving the dual goals of protection, restoration, and social value activation. It should be noted that the framework does not separately list specific protection and restoration technical measures because there are significant differences in the types of diseases and structural states of different buildings. Technical measures need to be formulated based on the measured data of individual buildings. The “lowest intervention level decision” focused on in this study is precisely to provide decision-making basis for the precise selection of protection and restoration technologies and the delineation of intervention scope in the future. Its core goal is still to serve the long-term protection and dynamic inheritance of historical buildings.

This study proposes a framework and method for selecting the minimum intervention level for historical buildings. Taking the historical buildings along the central axis of Beijing as an example. This study established a minimum intervention system framework for historical buildings (5 levels) and selected the minimum intervention evaluation factors (3 target levels, 9 criterion levels, and 29 factors) through literature

analysis. Using the AHP and FCE, the intervention levels of 14 historical buildings along the central axis of Beijing were ranked and compared, and they were divided into four categories in a ratio of 2:1:10:1. The results also confirmed that the intervention methods for historical buildings along the Beijing central axis were minimal interventions. This study provides a minimum intervention approach for the reuse of historical architectural complexes, and offers ideas for optimizing their reuse and sustainable development.

Data availability

All the data generated or analyzed during this study are included in this published paper.

Received: 9 September 2025; Accepted: 13 January 2026;

Published online: 21 January 2026

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Acknowledgements

This paper is financially supported by R&D Program of Beijing Municipal Education Commission (KM202211417007).

Author contributions

Yan zhang wrote the manuscript.

Competing interests

The author declares no competing interests.

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