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Research on Measuring Methods and Influencing Factors of Spatial Damage Degree of Historic Sites: A Case Study of Three Ancient Cities in Shanxi, China

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Abstract: Historic sites are important components of every city's cultural history because they preserve rich historical knowledge and distinctive values passed down from previous generations to the present. Due to the progress of urbanization and modernization, many historic sites face pressure from damage and transformation. In this paper, a method for assessing cultural heritage damage was developed to measure the extent of spatial damage in historic sites. Using sample data obtained in Xiyang, Qi, and Xiaoyi, all historic cities in Shanxi Province, Mainland China, and combined weights were estimated using the Delphi technique and the CRITIC weight method. Following this, the Spatial Damage Degree Model (SDDM) based on K-means cluster analysis and K-nearest neighbor (KNN) classification was developed. The findings show that the model efficiently solves the problem of assessing spatial damage levels in historic sites. Through multiple linear regression analysis, it was shown that the damage to historic sites was predominantly caused by three factors: natural erosion, construction damage, and planning and policy. SDDM was used to calculate the spatial damage levels of historic sites, allowing conservators to fully comprehend the features and concerns related to historic sites. As a result, more scientific and rational preservation approaches can be developed, improving the efficiency of historic site restoration and conservation, and encouraging the sustainable development of urban and rural heritage.

Keywords: historic sites; spatial damage degree; K-means clustering; K nearest neighbor classification; damage factors

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Citation: Zhao, B.; Han, W. Research on Measuring Methods and Influencing Factors of Spatial Damage Degree of Historic Sites: A Case Study of Three Ancient Cities in Shanxi, China. *Buildings* **2023**, *13*, 2957. https://doi.org/10.3390/buildings13122957

Academic Editors: Dan Bompa, Cristina Coscia, Carla Bartolozzi and Daniele Dabbene

Received: 30 October 2023
Revised: 17 November 2023
Accepted: 24 November 2023
Published: 28 November 2023

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1. Introduction

Urban cultural heritage serves as a driving force, propelling sustainable urban development [1], with historic sites being vital constituents of this heritage. The renovation of these historic sites throughout the process of urbanization enhances the city's livability and distinctiveness. According to the International Council on Monuments and Sites (ICOMOS), conservation means the development of a location to preserve its "cultural significance" [2]. However, improper preservation could lead to spatial damage within these urban historic sites during their adaptive use. At present, China's commitment to cultural heritage protection is gaining significant recognition, but it is concurrently facing immense pressure due to the country's rapid development. While national and city-level authorities are increasingly focusing on cultural heritage and accelerating the implementation of protective legislation, cultural heritage sites are still suffering severe damage, with some historic sites rapidly deteriorating. Additionally, given China's specific national conditions and development stage, the task of cultural heritage protection has to be carried out in phases due to limited material resources, preventing comprehensive coverage of all historic sites. To resolve these issues, it is crucial to understand the meaning of heritage value, as well as related matters like value assessment. This insight will facilitate research into the scope of damage across diverse historic sites. By distinguishing between the levels of damage at various historic sites, cities can optimize the scheduling of protection and development initiatives. This approach not only boosts the efficiency of heritage restoration but also aids in the prudent use of human and material resources.

Historic sites are more than just standalone structures; they are urban and rural landscapes that reveal unique cultures, significant developments, and historical events [3]. The concept of historic sites has been developed based on this perspective. From the Venice Charter of 1964 to the Washington Charter of 1987, the definition of historic sites has evolved from "the area surrounding a historic building" to "large and small areas of historical significance in a town, encompassing the old town center and other areas of historical interest" [3,4]. Heritage is inseparable from the history they have witnessed and the context within which they were conceived or built, underlining the importance of research on historic sites.

Firstly, the term 'damage' is employed to denote the physical harm inflicted upon historic sites, attributable to both natural elements such as weathering, floods, and seismic activity, and human actions like deliberate damage or overuse. This definition is framed with respect to the integrity and authenticity of these historic sites, crucial criteria in assessing their historical and cultural significance. Secondly, the concept of spatial damage pertaining to historic sites is a composite one that encapsulates the physical space of these sites along with its component relationships. Specifically, it takes into account not only the physical damage to the site itself, but also its ramifications on the surrounding environment. This encompasses the disruption of the spatial configuration, architectural infrastructure, and the interplay between different buildings and the site, as well as the architectural style of the site itself.

When observing global research trends on this subject, the primary emphasis has been placed on damage assessment, technological methods of detecting damage, and factors contributing to the deterioration of historical buildings, relics, ancient city walls, and other cultural heritage. However, there is a noticeable lack of research concerning the damage to larger regions, such as historic sites and major historical urban centers. Although most studies on historic sites aim to pinpoint challenges and propose solutions, there is a conspicuous absence of quantitative methods or indicators for evaluating the geographical scale of damage to historic sites. Several factors contribute to this situation. To begin with, the study of historic sites is a multidisciplinary endeavor spanning fields such as architecture, urban planning, sociology, economics, and so on. This makes it a more complex task compared to the study of individual monuments. Secondly, monuments being tangible objects make it easier to detect, measure, document, and monitor their damage. In contrast, historic sites are more abstract. They encompass elements such as spatial architecture, environmental factors, and historical evolution, which makes it challenging to clearly define and estimate their value and extent of damage.

There is considerable international research on cultural heritage. Earlier research on the assessment of damage to cultural heritage mainly focused on the post-disaster assessment, mostly after natural disasters [5,6], fires [7], and wars [8–10]. This is mainly conducted by recording the degree and spread of damage to heritage in detail and establishing archives or databases [9,11,12]. In terms of the recognition of damaged heritage, the recognition method has changed from the traditional on-site visual inspection method to intelligent recognition methods such as remote sensing image technology [13,14], UAV technology [15], automatic image processing technology [16], and photogrammetry [17].

In recent years, many scholars have explored the methods of cultural heritage damage assessment [18] and applied them to heritage protection. Zhang (2021) improved the artificial intelligence algorithm to build the CHDA application [19], which accurately locates the damaged areas of cultural heritage by exploring image data posted on social media during disaster events. Tejedor et al. (2022) analyzed the degree of damage to cultural heritage through non-destructive testing (NDT) technology [20–24]. P. Jouan (2019) improved the HBIM model and applied the digital twin (DT) principle to predict threats to heritage integrity through the analysis and simulation of data collected by field sensors and to support site managers in the preventive protection of their assets. Many scholars have proposed drawing the risk map of cultural heritage through WebGIS [25,26] and applying it to the management, monitoring, and prediction of cultural heritage. The GreatWatcher system, based on mobile crowd sensing (MCS) techniques and a deep learning algorithm, was developed by Wang (2019), focusing on big data collection and damage detection for the Great Wall [27]. Baharak et al. (2021) conducted a review and outlook on the heritage assessment framework (HIA). They also discussed the key role of the "impact assessment" phase in the overall HIA procedure and seeks to explore the several common EIA impact assessment methods and their applicability to the cultural World Heritage properties [28]. Cucco, P. (2023) developed an evaluation method for changes in the facades of historical buildings based on human behavior that has a potential impact on cultural heritage [29].

Furthermore, the combination of cluster analysis and machine learning (ML) with heritage protection has become a prevailing research trend. This integration allows cluster analysis and machine learning to play a crucial role in heritage classification and the formulation of tailored protection measures for various classifications. Agapiou (2016) obtained data from remote sensing images, used AHP analysis and cluster analysis to classify more than 150 protected monuments and sites in Paphos, Cyprus, and analyzed the possible natural and man-made threats to them [30]. Jboor et al. (2019) proposed a new image inpainting framework for visual cultural data that uses a divide-and-conquer strategy based on clustering [31]. Jiang et al. (2022) divided the sub watershed dataset of the Beijing Great Wall Cultural Area into five groups through K-means clustering calculation, and proposed different management strategies for different types of sub watersheds to adapt to the unique socio-economic and biophysical conditions of each watershed [32]. Solla M. et al. (2020) used KNN classifier to classify the facade pathology of historical buildings, combined with non-destructive testing technology, to improve the efficiency of recording historical building information [33].

While research on quantitative assessment methods for cultural heritage damage is emerging, there is limited literature on measurement methods for assessing the extent of damage in the comprehensive context of historic sites. Ultimately, only the calculation and monitoring of the damage degree of cultural heritage cannot provide a sustainable cultural impetus for the sustainable development of urban heritage, and it needs to be extended to the completely historic sites with protection value. The cultural elements of historic sites are mainly composed of various types of cultural heritage; therefore, the damage factors are more complicated. Therefore, on this basis, this paper draws on previous studies on the assessment of cultural heritage damage, learns assessment methods and ideas, and constructs the spatial damage degree model (SDDM) of historic sites. The model uses a comprehensive evaluation method, cluster analysis, machine learning, and multiple linear regression analysis to comprehensively consider the cultural spatial value and damage factors of historic sites; and, to a certain extent, solve the problems of difficult data acquisition and complicated analysis methods due to the large content of historic sites.

The primary contribution of this study is to broaden the assessment of historical heritage damage from the previous focus on individual buildings to a comprehensive examination of buildings, streets, fabrics, and historical environmental elements within historic sites. This culminates in the establishment of the Spatial Damage Degree Model (SDDM) for historic sites. This is accomplished by reviewing and assimilating previous research methods and ideas, in order to select the most appropriate methods for establishing the model in this study. The paper mainly focuses on the following issues:

1. Exploring the method of establishing the index system of measuring the spatial damage degree of historic sites;
2. Classifying the degree of damage of historic sites units of the three research areas based on K-means clustering analysis;
3. Training and testing the clustering results based on the K-nearest neighbor (KNN) classifier;
4. Using multiple linear regression equations to analyze the damage factors of historic sites.

2. Methods and Materials

2.1. Research Methods

To establish the SDDM in this study, data mining and analysis are applied to calculate the spatial damage degree of historic sites in Xiyang Ancient City, Xiaoyi Ancient City and Qi Ancient City. This model has the potential to be utilized in the future for predicting the spatial degree of damage for other historic sites.

The research method mainly consists of six steps, which are as follows:

1. Constructing an indicator system for measuring spatial damage degree;
2. Determining the indicator weights;
3. Calculating the comprehensive evaluation value;
4. Classifying the damage degree of samples in the research areas through K-means clustering analysis;
5. Verifying clustering results using the K-nearest neighbor classifier;
6. Using multiple linear regression equations to analyze the damage factors of historic sites.

2.1.1. Step 1: Construction of Spatial Damage Index System

The specific number of indicators currently used in heritage preservation can be hard to quantify, as it can vary greatly depending on the country and the type of cultural heritage in question. However, there are many key criteria used globally, including World Heritage Lists, national registers, Sites of Special Scientific Interest, National Historic Landmarks, National Trusts, National Monuments, European Heritage Labels, and more, as mentioned above. Furthermore, many countries have their own additional systems and criteria for heritage preservation, adding to the breadth and diversity of these indicators.

In determining these indices, the authors referred to related research both domestically and abroad, and made choices according to our research objectives and actual conditions. In this study, the validation of a site as historic relied on the authenticity and integrity of its historical and cultural spaces as well as its heritage. Consequently, the assessment of spatial damage relies heavily on the extent of damage to these attributes—integrity and authenticity. On this basis, predecessors have conducted extensive research on the evaluation of the spatial value of historic sites. The evaluation criteria for the evaluation system of Chinese historical and cultural cities include the degree of preservation of historical buildings, ruins, streets, and alleys [34]. The approval requirements for the World Cultural Heritage List include cultural relics, architectural complexes, and sites [35]. These guidelines form the foundation for the construction of the indicator system in this study. Wu (2015) utilized Kevin Lynch's Five Elements of Urban Design to establish an evaluation system for assessing the value of three historic sites in Guangdong, China [36]. Li et al. (2019) proposed a tripartite categorization of indicators: architectural heritage value, folk cultural value, and traditional production methods. This categorization comprises 16 sub-indicators including the degree of building preservation, building dimension, and the extent of environmental coordination [37]. Similarly, Liu et al. (2019) divided their evaluation indicators into four categories—historical authenticity, continuity of life, stylistic integrity, and renovation rationality—as per the Regulations on the Protection and Planning of Chinese Historical and Cultural Cities [38]. Cheng (2016), on the other hand, created an indicator system that incorporated the living environment, traditional architecture, site selection patterns, and intangible cultural elements to assess the value of historic sites [39]. This study took a value assessment approach to examine the spatial damage of historic sites. Prior studies based on the value system have chosen static indicators like historical buildings, historical streets and lanes, and heritage. Given the characteristics of spatial damage in historic sites, the authors have incorporated a dynamic indicator—fabric evolution—to delineate the spatial damage in historical areas during their development and evolution, building on previous research. Afterwards, the authors used Kevin Lynch's five elements of urban design as a reference to subdivide these indicators into four classifications: node, path, edge, and district [40]. The 'node' encompasses buildings and courtyards, while 'path' signifies traditional streets and alleys in historic sites [41,42]. 'Edge' represents historical environmental elements like city walls and moats within these areas. Lastly, 'district' signifies the overall historical evolution of these areas. It is important to note that the categories of node, path, and edge are classified as static indicators, while district falls under dynamic indicators. These indices are crucial for reflecting the morphological and functional changes in historic sites in the context of historical transformations [43,44].

While this method lacks fixed standards, it is generally considered to be effective [45]. The indices we chose are commonly used and widely accepted in studies on historic sites, capable of comprehensively reflecting the characteristics and development of such areas.

Moreover, acquiring data is a vital aspect in the study. Current methodologies primarily include remote sensing technology and GIS, drone-based oblique photography, on-site evaluations, literature review, machine learning, and deep learning. The first four techniques are utilized in this study for data collection. Remote sensing technology and Geographic Information Systems (GIS) are employed to collect and scrutinize the spatial data of historic sites [46]. More specifically, the authors can discern and quantify damage by comparing images from various time frames. Drone oblique photography is used to obtain high-resolution 3D images of the terrain, architectural structures, and other surface features within the study area [47]. This procedure allows authors to directly assess research subjects and acquire data for modeling. While the advent of new technologies furnishes invaluable insights, on-site evaluations remain crucial. These physical inspections enhance our comprehension of the specific scenarios and impacts of spatial damage in historic sites. Furthermore, it is imperative to consult scholarly literature and devise indicator schemes grounded in prior research, while also aligning with individual research necessities. In the realm of data collection for spatial indicators of historic sites, machine learning and deep learning also show promise. Convolutional Neural Networks (CNN) can identify objects and features within images, contributing to the measurement of spatial damage [48]. The study anticipates further advancements in this domain in the future.

2.1.2. Step 2: Determine the Weight of Indicators

This step combined two methods (subjective and objective weights) to make it professional to some extent. The Delphi method and a small group decision-making technique were used in the subjective empowerment, and then a questionnaire survey and interviews were conducted among professionals in other to modify the index system. The objective weighting method used the CRITIC weight method, and assigned weights according to the comparison intensity and conflict of evaluation index values [49]. Finally, the weights obtained by the two methods were synthesized to obtain the final weight of each index.

1. Delphi Method

Delphi is an advisory decision-making technology summarized and proposed by the RAND Corporation in 1964 [50]. Its core objective or framework is to solicit the opinions of experts through several rounds of anonymous correspondence, to find the optimal or satisfactory solution for the group. The questionnaire designed in this study is a 5-point attitude scale, and the higher the score, the more positive the attitude toward the importance of this indicator. The interviewed group mainly consists of lecturers and professors in architecture and urban and rural planning, as well as staff members who have worked in design institutes for more than 5 years. The expert scoring form can be found in Appendix A.

2. CRITIC weight method

CRITIC (Criteria Importance Through Inter-criteria Correlation) weighting method is a kind of objective empowerment method. It uses a sequence of each value in the standard deviation and coefficient of correlation to determine the index weight [49]. However, in this method, the independence of the data and the preferences of the professional evaluators cannot be reflected in the weights. Therefore, the Delphi method was selected to modify the CRITIC weight method in the index weight determination method.

3. Multiplicative synthesis method

This method multiplied the weights of an indicator obtained by the Delphi method and the CRITIC weight method and then obtained the combined weights w_j according to Formula (1).

$$w_j = \prod_{k=1}^{q} \theta_j'(k) / \sum_{j=1}^{q} \prod_{k=1}^{q} \theta_j'(k) \tag{1}$$

Note: θ_j' is the product of the weight W_a obtained by the Delphi method and the weight θ_j obtained by the CRITIC weight method, and q is the number of indicators.

2.1.3. Step 3: Calculating Comprehensive Evaluation Value Q_i

Q_i (Formula (2)) was used to calculate the comprehensive evaluation value based on the weight of the quantitative results of historic sites' spatial damage. Q_i is the basis for subsequent K-means clustering analysis and the establishment of KNN prediction correction models.

$$Q_i = \sum_{i=1}^{n} w_i \cdot x_{ij}' \tag{2}$$

Note: Q_i is the comprehensive evaluation value, w_i is the combined weight value, x_{ij}' is the standardized values of various indicators, and n is the number of samples.

2.1.4. Step 4: Classifying the Damage Degree of Samples in the Research Areas through K-Means Clustering Analysis

The comprehensive evaluation value of each index of each plot on the historic sites obtained through the first three steps is the basic data set for the analysis of the fourth step. K-means clustering is a type of unsupervised machine learning algorithm used to classify objects into K different groups (clusters) based on certain features. The algorithm operates on the principle of minimizing the within-cluster variance, which is the sum of the squared Euclidean distances between each point and the centroid of its assigned cluster. The 'means' in K-means refers to the averaging of the data, i.e., finding the centroid [51]. The K-means clustering algorithm consists of the following steps [52]:

1. Initialization: Randomly select K points to serve as the initial centroids of the K clusters;
2. Assignment: Assign each data point to the nearest centroid. The measure of distance used is often the Euclidean distance;
3. Update: Calculate the new centroid (mean) of each cluster by taking the average of all the data points in the cluster;
4. Repeat steps 2 and 3 until the algorithm converges, i.e., the centroids do not change significantly, or a predetermined number of iterations are reached.

The clustering analysis formulas are as follows:

$$c_p = \frac{1}{N_p} \sum_{u=1}^{N_p} Q_{pu},\ p = 1, 2, 3 \ldots k \tag{3}$$

$$A = \sum_{p=1}^{k} \sum_{u=1}^{N_p} \left| Q_{pu} - c_{pu} \right|^2 \tag{4}$$

where N_p means that there are N_p data in the cluster center c_p, Q_{pu} means the uTH data in the cluster center c_p, and the iteration continues until it meets the termination condition that the sum of squared errors A (Formula (4)) converges [53]. Then we can obtain the final clustering center $c_1, c_2, \ldots, c_p$.

Additionally, the cluster number K value was selected according to the elbow rule, and the K value was set as 5 in this study. As is shown in Figure 1.

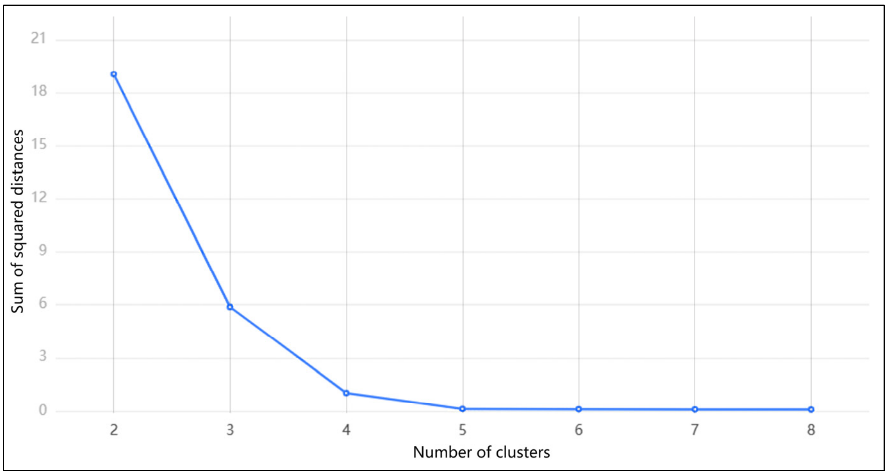


Figure 1. Cluster comparison chart (elbow rule). Note: This graph is utilized to determine the optimal number of clusters. The x-axis signifies the number of clusters, while the y-axis represents the K-means clustering loss function, depicted as the sum of squared distances from all samples to the center of their respective clusters. This is also known as the sum of squared errors. A higher value indicates better clustering effectiveness. The optimal number of clusters, as indicated by the point where the slope begins to flatten, is found to be 5.

In the study, the authors opted for K-means clustering over other clustering approaches due to its simplicity, efficiency, and suitability for our research. The benefits of K-means included its ability to partition the data into distinct groups based on the similarity of their features. This allowed for a meaningful categorization of the damaged areas, providing a clearer overview of the extent and degree of damage. It can also aid in identifying patterns or trends within the data, contributing to a more nuanced understanding of the spatial damage in the historic sites.

By using the K-means clustering, the authors were able to classify the spatial damage into distinct categories, providing a useful foundation for further analyses and interventions. The subsequent application of the KNN algorithm for validation further strengthened the robustness of their results.

2.1.5. Step 5: Verifying Clustering Results Using K-Nearest Neighbor (KNN) Classifier

The results obtained from the fourth step of clustering analysis are classified into 1–5 levels based on the degree of spatial damage in historic sites, from low to high. The higher the level, the greater the degree of spatial damage. Then the K-nearest neighbor (KNN) classifier was used to simulate and verify the classified data. The K-nearest neighbor (KNN) classifier is one of the commonly used classifiers in supervised learning [54]. Its principle is to classify the observations as the one with the highest proportion among the K closest observations. In the KNN algorithm, there are three commonly used distances, namely, Euclidean distance [55], Manhattan distance [56], and Minkowski distance [57]. Euclidean distance was adopted in this study. Let x_i be an input sample with p features, n is the total number of input samples, and p is the total number of features, then the Euclidean distance between x_i and x_l is:

$$d(x_i, x_l) = \sqrt{(x_{i1} - x_{l1})^2 + (x_{i2} - x_{l2})^2 + \ldots + \left(x_{ip} - x_{lp}\right)^2},\ i = 1, 2, \ldots, n;\ l = 1, 2, \ldots, n \quad (5)$$

The K-nearest neighbor (KNN) classifier divided the sample data into training data sets and test data sets, using class labels after the previous clustering algorithm, and is a "supervised" classification method. In the training process, the real category of each training sample is used to train the classifier, while in the testing process, the classifier is used to predict the category of each test sample [54]. The performance and accuracy of the

KNN classifier depend on the choice of K value and the distance measure applied. In this study, the cross-validation method [54] was adopted to select the optimal K value.

2.1.6. Step 6: Researching Method of Damage Factors of Historic Sites: Multiple Linear Regression Analysis

Multiple linear regression analysis is a statistical analysis method used to determine the interdependent quantitative relationship between two or more variables. Its core is to use multiple independent variables to jointly predict or estimate the trend of dependent variables [58]. Therefore, to clarify the damage factors and study the influence of the various factors on the spatial damage degree of historic sites, a multiple linear regression model was selected to analyze the influencing factors. The model equation is as follows (Formula (6)):

$$\gamma = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_n X_n + \varepsilon \tag{6}$$

where, γ is the dependent variable, representing the degree of spatial damage in historic sites; $X_1, X_2, \ldots, X_n$ is a series of factors affecting the spatial damage degree of historic sites; $\beta_0, \beta_1, \beta_2, \ldots, \beta_n$ is the regression coefficient, ε is the error term.

2.2. Data Sources and Study Area

2.2.1. Data Sources

The data collected from the three sample areas in this study are the basis for calculating the spatial damage degree. To ensure data accuracy, scientific validation, and comprehensive coverage, building contour data and road data from the OSM map were combined with field investigations, drone recordings, and the Baidu Street View map (2019). This facilitated investigations and statistical analyses of relevant indicators, including buildings, courtyards, and streets within the plots. Google Maps aided in the study of the spatial evolution process of buildings, streets and fabrics within the plots over the past ten years [14], and the quantitative value of the dynamic index of block damage degree was extracted. The data source is shown in Table 1. Seventy sets of data samples were collected in the three research areas for this study.

Table 1. Data sources.

Data Name	Data Type	Data Sources
Google Satellite Maps	Tif	Google Earth
Osm Building Outline Data	Osm	https://www.openstreetmap.org/ (accessed on 15 October 2022.)
Osm Road Data	Osm	https://www.openstreetmap.org/ (accessed on 15 October 2022.)
Baidu Streetscape Map	Map	https://map.baidu.com/ (accessed on 25 February 2023.)
CAD topographic map	Dwg	Local Housing and Urban-Rural Development Bureau
Third National Land Survey Data	Shapefile	Local Housing and Urban-Rural Development Bureau
Aerial view of the site	Jpg	On-site research (UAV)

2.2.2. Study Area

Three locations are strategically selected for this study. They are Xiyang Ancient City, Xiaoyi ancient City, and Qi ancient City, all in the Shanxi Province. The bases or criteria for their selection are their inherent richness in cultural history and heritage both tangible and intangible. They also include data samples such as buildings, streets, courtyards, etc., of different levels of damage degree, which are vital for this study. The location of the research areas is shown in Figure 2.

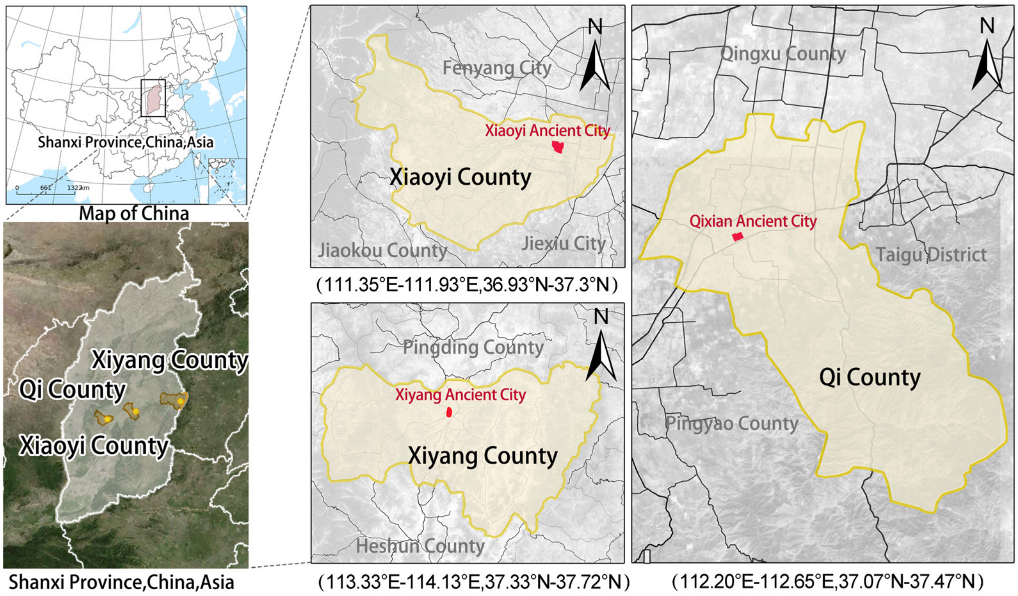


Figure 2. Location analysis diagram.

3. Results

3.1. Index System and Weight

3.1.1. Index System

The indicator system for measuring the degree of damage in historic sites is crucial for the preservation and restoration efforts of these valuable cultural heritage sites. According to the aforementioned method, the indicator system could be classified into two main categories: static indicators and dynamic indicators. Building upon this classification, urban design was further divided into four distinct categories, taking into consideration the unique characteristics of historic sites. These categories were based on the fundamental elements of node, path, edge, and district. Afterwards, several references were made to further refine the indicator system.

The 'node' encompassed six indicators: building roof, building feature, building function, building dimension, building structure, and courtyard form. The 'path' was characterized by three indicators: street coordination, street continuity, and street scale. The 'edge' pertained to the level of preservation of the enclosing boundary. The 'district', on the other hand, was measured by the degree of fabric evolution. Finally, a total of 11 indicators were identified. The data for seven indicators, including building roof damage degree, building dimension contradiction rate, damage degree of courtyard form, street scale damage degree, street continuity, enclosing boundary survivability, and fabric evolution degree, were obtained from Google Maps. The data for the indicators of building structural damage degree and building function change rate were mainly collected through field investigation. The data for the indicators of building feature damage degree and street coordination were obtained through a comprehensive evaluation of Baidu Street View map, UAV, and field investigation. The data acquisition for these indicators mainly relied on the observation method. The sources of indices data are shown in Table 2.

Table 2. The resources of indices.

Index Classification	Elements Attributes	Index Name	Resources
Static index	Node	Building roof damage degree [41]	Google Maps
		Building feature damage degree [59]	Baidu Street View map, UAV, and field investigation
		Building function change rate [60]	Field investigation
		Building dimension contradiction rate [59]	Google Maps
		Building structural damage degree	Field investigation
		Damage degree of courtyard form	Google Maps
	Path	Street scale damage degree	Google Maps
		Street coordination [36]	Google Maps
		Street continuity	Baidu Street View map, UAV, and field investigation
	Edge	Enclosing boundary survivability	Google Maps
Dynamic index	District	Fabric evolution degree	Google Maps

For more detailed information on the definition and calculation of these indicators, please refer to Appendix B. The specific organization of the indicator data can be found in Appendix C.

3.1.2. Weight Determination

Table 3 shows the combined weights of each index. From the table, the synthesis method uses the Delphi method to modify the weight from the CRITIC method to obtain a more realistic weight. Building feature is an index that can most directly reflect the damage situation in the evaluation system because its weight is the largest, 0.308. Courtyard form and street coordination follow in the second and third positions with weights of 0.222 and 0.186, respectively. The enclosed boundary mainly exists around the historic sites. At present, there are few relics of the ancient city walls, moats, and other surrounding boundaries, so their weight is also relatively large. The building function does not directly relate to the spatial damage of historic sites, so the weight is the smallest.

Table 3. Combined weight result.

Index Name	Delphi Method	CRITIC	Multiplication Synthesis
Building roof damage degree	0.064	0.089	0.050
Building feature damage degree	0.205	0.170	0.308
Building function change rate	0.048	0.021	0.009
Building dimension contradiction rate	0.072	0.029	0.018
Building structural damage degree	0.062	0.028	0.016
Damage degree of courtyard form	0.119	0.211	0.222
Street scale damage degree	0.050	0.055	0.024
Street coordination	0.108	0.194	0.186
Street continuity	0.073	0.022	0.014
Enclosing boundary survivability	0.091	0.137	0.111
Fabric evolution degree	0.108	0.044	0.042

3.2. Results of Cluster Analysis

According to the comprehensive evaluation value Q_i, the collected sample plots were divided into five clusters. Due to the randomness of the initial statistical centroid in clustering analysis, multiple analyses were conducted and validated by KNN classifiers, resulting in the highest accuracy set of classifications for constructing the SDDM. The process was finalized when there was no change in the cluster center or only a small change; the maximum absolute coordinate change in any centers is 0.000. It took six iterations to obtain the optimum result. The study included 70 sets of historic sites data graded from one to five, representing damage degrees from low to high. The segregations were made up of 22 sections in the first degree of damage, 26 sections in the second degree of damage, 14 sections in the third degree of damage, 7 sections in the fourth degree of damage, and 1 section in the fifth degree of damage. In determining the level of damage, the authors combined research and collected foundational data. The clustering results are shown in Figure 3.

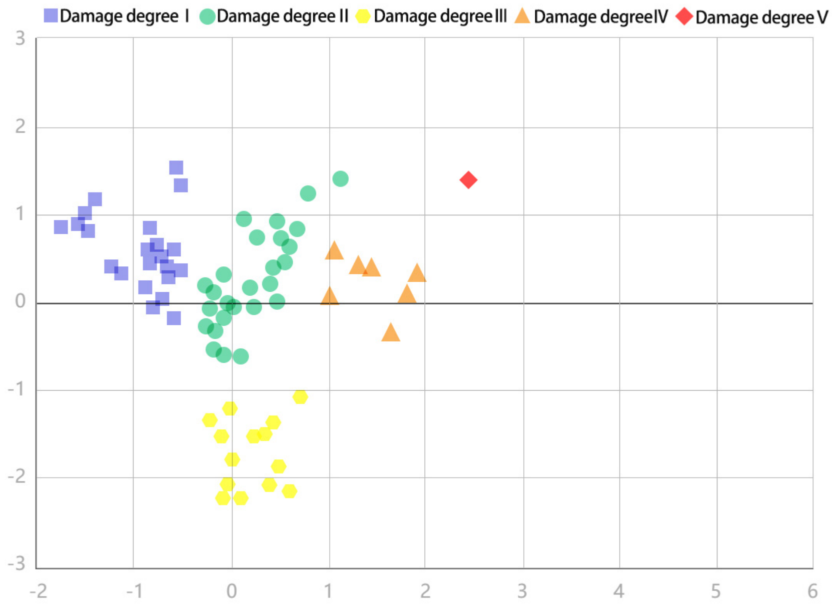


Figure 3. Damage degree clustering classification diagram.

Generally, the degree of spatial damage within historic sites tends to follow a specific pattern. The central areas typically exhibit a lower degree of damage, while the surrounding areas show a higher degree. In essence, the core areas of the historic sites tend to be less damaged, preserving diverse types of heritage effectively. Conversely, the boundaries of these sites often experience a relatively higher extent of damage, with numerous instances of demolition. Newly constructed buildings within these sites often display a stark contrast in both volume and style when compared to the existing historical structures.

Specifically, the northern region of Xiyang Ancient City has experienced significant damage, with one plot even reaching a damage degree of grade-5. This primarily manifests as the demolition of over 90% of the historical buildings within the plot. Furthermore, the size and structure of the newly erected buildings have undergone substantial transformations. The current architectural style is seriously inconsistent with the historical one, leading to a profound disparity in the aesthetic appeal of the region.

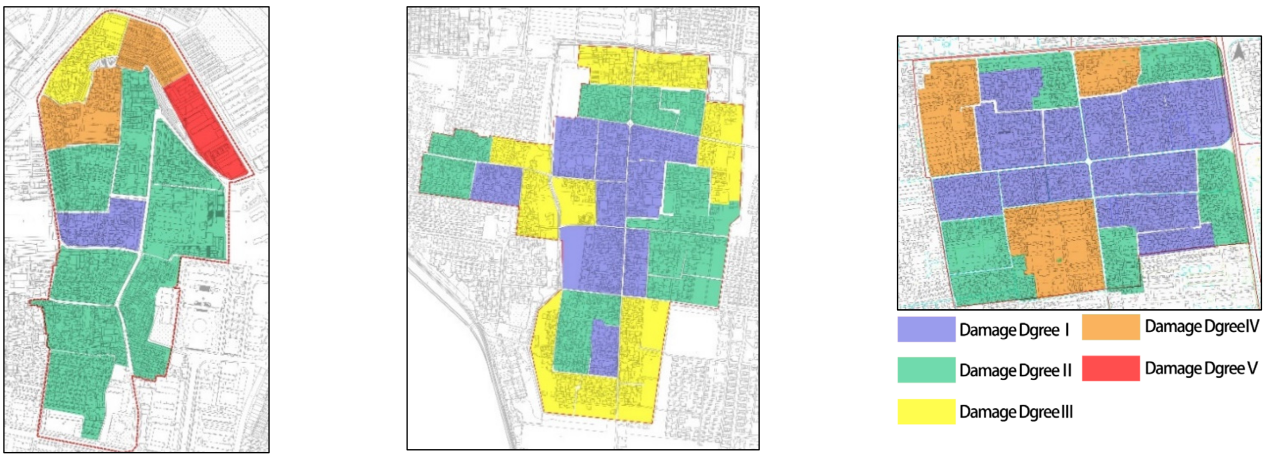
Two additional plots in Xiyang Ancient City, primarily located in the north, have suffered grade-4 damage. Similarly, five plots in Qi Ancient City, spread across the northern and southern border areas, have incurred grade-4 damage. Plots that fall into this category are marked by the demolition of more than 60% of historic buildings, substantial damage to the overall fabric of the area, and a considerable proliferation of modern-style structures. Despite the preservation of several historical buildings, the quality of these structures is generally poor and their appearance is unremarkable. Furthermore, there is a significant lack of coordination and continuity among the street layouts, and the function of these buildings has drastically shifted.

A plot in the northwest corner of Xiyang Ancient City exhibits grade-3 damage. Similarly, 13 other plots scattered along the northern and southern perimeters, and in the middle of the western side of Xiaoyi Ancient City, also show grade-3 damage. The primary indication of this level of damage is the unchanged land fabric, minimal harm to the courtyard structure, and building dimensions that align with those of the original ancient constructions. Modern-style edifices constitute a significant portion of the total building area, while historical buildings with substandard appearances make up 30% to 60% of the overall area. The majority of these grade-3 damaged plots encompass renovated private residences, serving predominantly as residential spaces. Despite the good structural quality of these buildings, their aesthetic appeal is lacking, and there is a noticeable lack of harmony between the streets and alleyways.

Eight plots in Xiyang Ancient City exhibit grade-2 damage, comprising 60% of the total plots. These are primarily situated in the central and southern parts of the ancient city. Likewise, twelve grade-2 damaged plots can be found in Xiaoyi Ancient City, mainly located to the east and north of the third-level damaged plots. Qi ancient city harbors six second-level damaged plots, chiefly positioned in the four corners of the city. These second-degree damaged plots retain the fabric and style of their historical counterparts, preserving the form of their courtyards. However, 20–30% of the building volume and functions have altered, resulting in less desirable features. Despite the presence of some modern-style buildings, which may somewhat compromise the integrity and authenticity of these plots, the overall style of the grade-2 damaged plots is more harmonious. They exhibit higher street continuity and the building scales are appropriate.

In the heart of Xiyang Ancient City, there is one plot with grade-1 damage. Additionally, there are 10 and 11 such plots in Xiaoyi and Qi Ancient Cities, respectively, mostly concentrated in their central areas. These sites with grade-1 damage are primarily characterized by the well-preserved structure of their buildings, appropriate scale, and an overall style that is well-coordinated. Buildings with substandard style account for less than 20% of the total construction area, while the courtyard form remains largely preserved. Despite the minimal overall damage, certain building elements like doors, windows, and interior decorations have not been fully protected. These are crucial aspects that require protection and enhancement in the future.

Generally speaking, the ancient city of Qi boasts the highest degree of preservation and the least damage, whereas the ancient city of Xiyang has suffered the most damage. The classifications of damage degree among the three historic sites within this study region are relatively concentrated, as illustrated in Figure 4.



(**a**) (**b**) (**c**)

Figure 4. Classification results of spatial damage degree of historic sites. (**a**) Cluster Analysis Results of Xiyang Ancient CityXiyang Ancient City. (**b**) Cluster Analysis Results of Xiaoyi Ancient City. (**c**) Cluster Analysis Results of Qi Ancient City.

3.3. KNN Verification Analysis Results

Through the K-nearest neighbor (KNN) classifier, the data were divided into a 70% training set and a 30% validation set, and the model evaluation results were obtained. Table 4 shows the prediction evaluation indicators of the training set and testing set, and measures the prediction effect of the K-nearest neighbor (KNN) through quantitative indicators. Among them, the hyper parameters can be adjusted continuously through the evaluation index of the cross-validation set, and a reliable and stable model can be obtained.

Table 4. KNN accuracy testing results.

	Accuracy Rate	Recall Rate	Precision Rate	F1
Training set	0.939	0.939	0.925	0.93
Testing set	0.81	0.81	0.695	0.738

Note: Accuracy is the proportion of the predicted correct samples in the total samples; the recall rate is the proportion of predicted positive samples in the results of actual positive samples; the accuracy rate is the proportion of predicted positive samples that are positive samples; F1 is the harmonic average of accuracy rate and recall rate.

Per the results in Table 3, the proportion of the predicted correct samples accounted for 81% of the total samples. For the results of the actual positive samples, the proportion of predicted positive samples, thus, the recall rate, was 81%, the accuracy rate was 69.5%, and the harmonic average of the accuracy rate and the recall rate was 73.8%. In the future, the results obtained by the K-nearest neighbor (KNN) classifier can be used as a reference to accurately protect small plots in historic sites.

3.4. Linear Regression Analysis Results

In the regression analysis, the index established in Step 1 is divided into four dimensions: building component, feature and form, building land use, and building fabric. This method, which categorizes indicators into four distinct groups, primarily serves to decrease the number of variables involved in regression analysis [61]. By doing so, it enhances the model's interpretability and simplifies the process of deciphering the results [62]. The classification is detailed as follows. (1) Building Components: This category amalgamates the 'building roof' and 'building structure' indicators, primarily focusing on the building's physical aspects. (2) Feature and Form: This category encompasses three indicators—architectural feature, courtyard form, and street coordination. These indicators collectively address the buildings and sites' overall aesthetics and form. (3) Building Land Use: This category comprises three indicators—building dimension, building functions, and the enclosing boundary. The focus here is chiefly on the buildings' layout and land use. (4) Building Fabric: This category integrates three indicators—fabric evolution, street scale, and street continuity. The primary concern here is the fabric evolution degree, which mirrors the spatial changes and evolution level in historic sites, serving as a crucial factor in assessing the extent of spatial damage.

According to the analysis, the significance of multiple linear regression is 0.000, indicating that there is a significant linear relationship between the model and the spatial damage degree of historic sites, which is conducive to further research on the damage factors of historic sites. According to the significance results, the influence degree of each variable in descending order is as follows:

- Enclosing boundary survivability (X_8);
- Street coordination (X_5);
- Building feature (X_3);
- Street continuity (X_{11});
- Fabric evolution (X_9);
- Building function (X_7);
- Building roof (X_1);

- Building structure (X_2);
- Courtyard form (X_4);
- Street scale (X_{10});
- Building dimension (X_6).

The significance of enclosing boundary survivability (X_8), street coordination (X_5), and building feature (X_3) are all less than 0.05, indicating that these three indexes have the greatest impact on the damage of historic sites. The significance of the five indexes of street continuity (X_{11}), fabric evolution (X_9), building function (X_7), building roof (X_1), and building structure (X_2) are all less than 0.5, indicating that the damage to the historic sites is not significant, but has a certain explanatory role. The three factors of courtyard form (X_4), street scale (X_{10}), and building dimension (X_6) are not significant. The result of multiple linear regression analysis is shown in Table 5.

Table 5. Regression coefficient table of influencing factors of spatial damage degree of historic sites.

Variable Class	Independent Variable	Standardization Coefficient	Significance	VIF
Building component	Building roof X_1	0.114	0.296	3.595
	Building structure X_2	0.222	0.331	15.696
Feature and form	Building feature X_3	−0.334	0.048	8.399
	Courtyard form X_4	−0.076	0.543	4.750
	Street coordination X_5	−0.378	0.001	3.782
Building land use	Building dimension X_6	−0.028	0.903	16.624
	Building functions X_7	−0.097	0.286	2.492
	Enclosing boundary survivability X_8	0.728	0.000	1.443
Building fabric	Fabric evolution X_9	−0.093	0.278	2.235
	Street scale X_{10}	0.028	0.684	1.443
	Street continuity X_{11}	0.144	0.181	3.469

Note: VIF (variance inflation factor) is used to measure the covariance of the independent variable. The larger the value, the more serious the covariance is. The standardized coefficient is the coefficient obtained after standardizing the data.

4. Discussion

4.1. Application and Deficiency of SDDM

4.1.1. Application of SDDM

Through field investigation and map observation of Xiyang, Xiaoyi, and Qi ancient cities, the basic data sample required for the establishment of the comprehensive model (SDDM) have been obtained. Matlab can be used to write the instruction codes for all kinds of data under the established index system, including various index algorithms, weight calculation, and clustering algorithms. By collecting the data in Appendix C and following the calculation method in Appendix B, other historic sites can use SDDM to determine the level of damage to the target plot, thus developing targeted update and renovation strategies.

4.1.2. Shortcomings and Improvement Direction of SDDM

1. The objectivity of data collection needs to be strengthened.

The spatial damage degree model (SDDM) of historic sites lacks quantitative data support. Some indexes such as the damage degree of building features and the coordination degree of streets are determined by subjective evaluation; therefore, there is some subjectivity and uncertainty in the practical application process. To improve the reliability and scientific proof of the model, it is necessary to establish a set of systematic data acquisition and analysis methods to obtain more accurate and objective damage-evaluation standards.

2. Maintenance and repair should be taken into account.

The spatial damage degree model (SDDM) of historic sites does not consider their maintenance and restoration. The extent of damage to historic sites is not only related to their past damage, but also to their maintenance and restoration. Therefore, it is necessary to introduce the maintenance and restoration of historic sites as evaluation indicators and combine the heritage assessment method (HIA) [63] to evaluate the damage degree of historic sites more comprehensively.

3. The information and database of the system need to be sorted out.

The spatial damage degree model (SDDM) of historic sites lacks a comprehensive reference database in practical application. The evaluation of the damage degree of historic sites is a complicated process therefore needs lots of reference data to support it. However, the accuracy of the evaluation results is limited by the lack of detailed reference data in the current model of historic site damage degree. Therefore, one of the directions of improvement is to establish a comprehensive reference database and collect and collate the relevant information of historic sites, to provide for the use of evaluation models.

4.2. Universality of SDDM

In the course of our study, the authors deliberated on the varying degrees of damage in our selection of research areas. This led us to choose three ancient cities, each representing a different level of devastation, as our case studies. The varying degrees of damage were taken into account through our carefully designed indicator system and data normalization process. This approach allowed us to address the inherent complexities of studying sites with a spectrum of damage severity, from high to low. Here is how:

Damage Assessment: The degree of damage to building roofs, structures, style, and courtyard form can be used as a measure of physical integrity, which is universally applicable. Sites in other parts of the world may have different architectural features, but the concept of assessing physical damage remains the same.

Inconsistency and Change: The degree of inconsistency in building volume and the degree of change in building function can be interpreted as measures of authenticity and continuity in use, respectively. These are important considerations in any historic site, regardless of its geographical location.

Urban Fabric: The degree of coordination, continuity, and scale of streets and alleys, as well as the degree of preservation of surrounding boundaries, can be seen as measures of the site's relationship with its urban environment. This is relevant for historic sites embedded within a city or town.

Texture Evolution: The degree of texture evolution can be used as an index of change over time. In other contexts, this might be interpreted differently depending on the local historical and cultural factors.

In terms of methodology, clustering analysis and KNN validation are generalizable techniques that can be applied in any context, given that the data collected are appropriate and sufficient. It is important to underscore that the impact of our study, though generally applicable, may be nuanced by the specific degree of damage in each individual city [64].

4.3. Progressiveness of SDDM

The potential of research in the quantification of spatial damage of historic sites lies in its ability to provide a comprehensive and quantifiable measure of the level of damage that has occurred. This is particularly important as it allows for the prioritization of conservation efforts, as well as enabling the analysis of damage trends over time, which can inform future preservation strategies.

Compared to other methodologies in the field, such as non-destructive testing technologies, Historic Environment Records (HER), Heritage Impact Assessments (HIA), Historic Building Information Modeling (HBIM), and Mobile Crowd Sensing (MCS), spatial damage quantification offers a unique perspective. While non-destructive testing, HER, HIA, and HBIM offer invaluable insights into the state of historic sites and buildings, they predominantly focus on individual cases or specific aspects of preservation. Mobile crowd sensing, on the other hand, leverages the power of the public to gather data but may lack the precision and thoroughness that a dedicated measurement approach can provide. The spatial damage quantification research, meanwhile, allows for a broader, more encompassing view of damage across different historic sites, providing a more holistic assessment.

In terms of the responsibilities of this research in the management of historic assets, territories, and sites, they are multifaceted. Firstly, by providing quantitative data on damage, it can aid in the prioritization of resources for conservation efforts. It can help identify sites that are in dire need of restoration or preventive measures, thereby contributing to the effective allocation of resources. Secondly, it can serve as a valuable tool for policy-making. By analyzing the trends and patterns of damage, policy-makers can formulate more effective strategies for historic sites preservation. Lastly, this research can contribute to raising public awareness about the state of historic sites. By presenting clear, quantitative data on the extent of damage, it can underscore the urgent need for preservation efforts and foster greater public involvement in conservation.

4.4. Study on the Influencing Factors of Spatial Damage in Historic Sites

The evolution of historical and cultural spatial forms is the result of several subjective and objective factors. In different periods, various dynamic factors have different effects on historical and cultural spatial forms.

4.4.1. Natural Erosion

Natural erosion plays a significant role in damaging cultural elements at historic sites, which encompasses natural disasters, environmental pollution, and the wearing effects of time. Natural disasters such as intense wind and heavy rainfall can trigger the falling off of shingles and connecting roof parts, thereby diminishing the roof's water resistance and causing leaks. Earthquakes, on the other hand, can instantaneously damage a building's structure [65]. Environmental pollution can directly impair the material composition of cultural heritage. For instance, in urban settings, air pollutants can interact with building surfaces, resulting in the corrosion of stone and metal, which, in turn, damages the buildings' appearance and structure. Aging and corrosion of building materials also occur over time due to environmental pollution [66]. Roof weeds are a primary factor in structurally damaging roofs.

In Xiyang Ancient City, the plots with the highest degree of roof damage represent 15% of all roofs, with weeds causing 80% of the damage. In Xiaoyi Ancient City, the plots with the most substantial roof damage constitute 25% of all roof damage, with 60% resulting from natural erosion and 40% from human activities. In the ancient city of Qi, the most significantly damaged roofs make up 13% of all roof damage, with 90% caused by natural factors.

4.4.2. Construction Damage

Aspects of human development deemed positive and progressive—construction, cultivation, and expansion—equally threaten the longevity and security of cultural heritage [67]. During urban renewal, extensive demolition, reconstruction, and renovation of historic sites have been implemented to enhance the city's image and economic efficiency. Efforts have been made to increase land utilization and development potential in the land market, leading to the demolition and reconstruction of historical buildings with outdated uses that no longer meet modern societal needs. As a result, modern buildings have emerged in originally continuous streets, changing their architectural function and style and disrupting the integrity and continuity of these historic sites. Furthermore, to cater to traffic needs and economic interests, numerous streets in these historic sites, such as Xiyang's ancient city's main streets, were converted into wide straight streets or shopping centers. This led to the disappearance of the original zigzag fabric, rendering the streets monotonous.

Moreover, in the midst of urbanization, the drastic population increase necessitates new land development and construction of new buildings and infrastructure. This often results in the damage of historic sites' fabric. The original historical buildings on Xiyang Ancient City's northeast side were torn down and replaced by high-rise residential buildings. The discordance between the old and new buildings starkly separated the fabric and style of the ancient city. In the ancient city of Qi's northwest corner, a large number of historical buildings were also demolished, severely damaging the continuity of the entire plot. Due to inappropriate measures in the protection planning of Xiaoyi Ancient City, original buildings with superior features in the western district of the county government were demolished and reconstructed, failing to maintain the fabric of the ancient city, as shown in Figure 5.

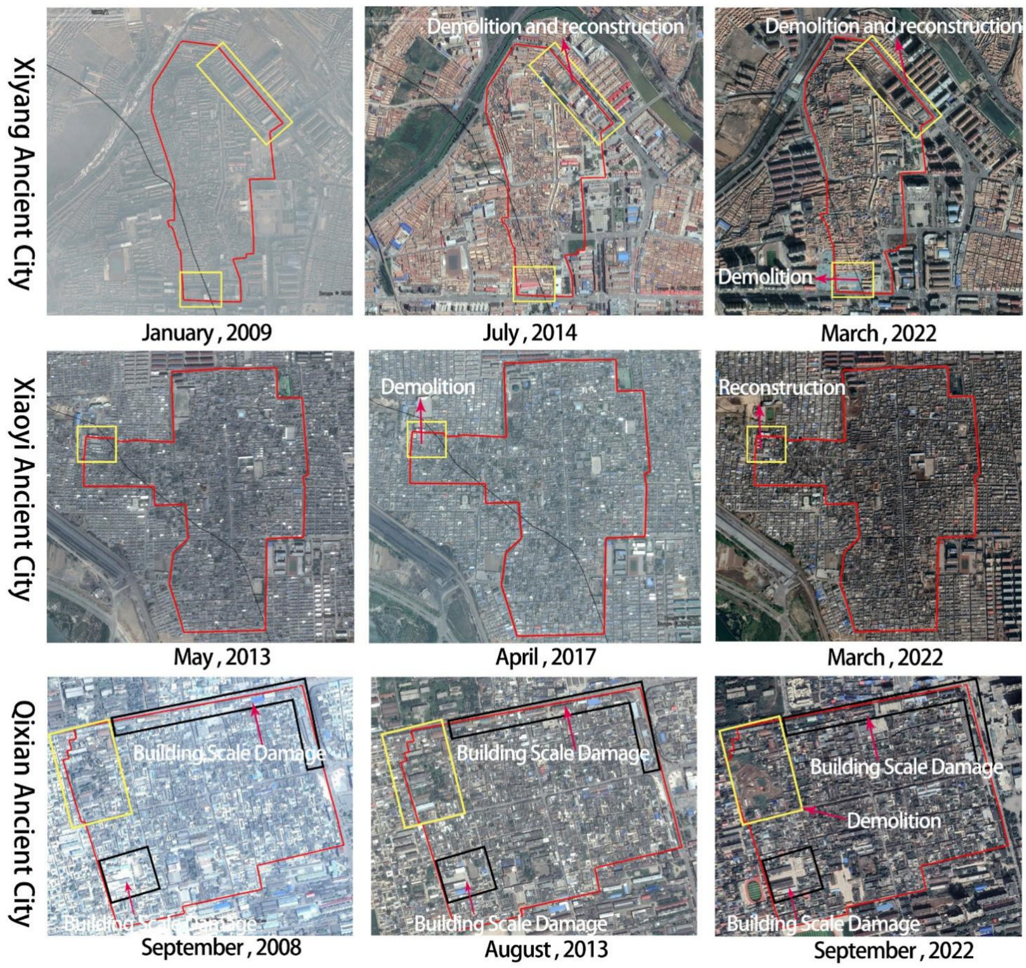


Figure 5. Building fabric damage analysis diagram.

4.4.3. Planning and Policy

Inadequate policies and regulations are significant contributors to the degradation of historic sites. Large-scale urban renewal or reconstruction, often driven by policy, can result in substantial damage to the distinctive style and fabric of these sites. The influx of tourists due to the development of tourism also exerts pressure on the preservation of the environment and buildings within these sites. Moreover, if penalties for illegal construction are insufficient, or if regulatory authorities lack effectiveness, historic sites may suffer from irreversible damage. This includes the damage of the original layout and alterations to the historical environment. Key characteristics of such damage include: (1) Significant alterations to the fabric of historic sites; (2) Extensive damage from building reconstruction efforts along the streets; (3) Demolition of certain areas to create public spaces.

5. Conclusions

The study developed a comprehensive model, known as the Spatial Damage Degree Model (SDDM), which measures the spatial damage level of historic sites. This model ingeniously integrates various methods, including the Delphi method, CRITIC weight method, K-means clustering analysis, and K-nearest neighbor (KNN) classification method. To investigate the factors contributing to spatial damage in historic sites, the authors employed multiple linear regression analysis. The primary conclusions drawn from this study are as follows:

1. The development of the Spatial Damage Degree Model (SDDM) for historic sites represents a significant innovation in traditional preservation efforts. This model not only provides a precise assessment of the spatial damage degree of historic sites, facilitating the formulation of accurate conservation strategies, but it also fills an existing gap in quantifying spatial damage within this field. This is a crucial step forward in historic site preservation, as it allows for more targeted and effective conservation actions;
2. The study revealed that the degree of spatial damage tends to be higher around the periphery and lower at the center of the area. In the Xiyang Ancient City, the first level of damage accounts for 7.69% of the total area, the second level for 61.53%, the third level for 7.70%, the fourth level for 15.38%, and the fifth level for 7.70%. In the Xiaoyi Ancient City, the first, second, and third levels of damage account for 28.57%, 34.29%, and 37.14% of the total area, respectively. Meanwhile, in the ancient city of Qi, 50% of the total area suffered first level damage, 27.27% second level damage, and 22.73% fourth level damage. Overall, Qi Ancient City has been best preserved and restored, while Xiyang Ancient City has sustained the most damage. The selection of the study area considered varying degrees of foundational damage. Incorporating these foundations into the development of the indicator system, and subsequently standardizing the indicators, allows for the mitigation of differences in the original quality of the sample area. Thus, the SDDM model has universal applicability. However, it should be noted that while our research model is generally applicable, it may require adjustments depending on the specific degree of damage in each city. Therefore, in application, the model can be modified by adjusting the indicator system and other methods as needed;
3. The spatial damage degree of historic sites is affected by the coupling interaction of multiple factors, including natural erosion, construction damage, and planning and policy issues. Natural erosion encompasses elements such as natural disasters, environmental pollution, and the wear and tear of time, and its impact on historic sites is an objective reality. Damage caused by construction is predominantly due to a lack of awareness among residents and inappropriate urban renewal practices, making it a subjective issue. Inadequate planning and lack of policies significantly impact the spatial damage of historic sites, as these factors determine the adherence to, and legitimacy of, preservation efforts for these sites. These are the primary areas that require improvement in the future;
4. The application of SDDM can be broadened by implementing the following strategies. (1) Detailed Instructions for Each Step: Expand the usage of SDDM by providing a comprehensive guide for each step. This study offers definitions and calculation methodologies for each indicator, along with exemplar tables for data collection and arrangement (such as Appendices B and C), which can significantly aid users in data gathering. Additionally, the paper outlines the process of using cluster analysis and how to determine K values (elbow rule). (2) Develop and Refine Indicator Adjustment Guidelines: In the future, the creation of guidelines for adjusting indicators can be incorporated. This can take into consideration various factors such as environmental conditions, local regulations, or community participation [68]. Consequently, the indicator system can be modified based on specific historic sites. (3) Diversification of the Model: Consider integrating SDDM with other evaluation models (for example,

ecosystem service evaluation models, landscape value evaluation models, etc.) to generate a more comprehensive and diverse evaluation system. This could enhance the model's versatility and applicability. (4) Development of Online Tools: Creation of online tools or mobile applications could make SDDM more readily accepted and utilized by the public. This not only makes the model more accessible but also encourages its widespread use for historic sites evaluation.

Author Contributions: All authors contributed to the paper. W.H. proposed the idea of this article and was responsible for reviewing and editing it. B.Z. was responsible for writing and data analysis. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the Research on the Characteristics and Protection Methods of Salt Erosion and Weathering Diseases in the City Wall of Northern Jin and Ming Dynasties, Shanxi Province Natural Science Research General Project (grant number: 202203021211171), and the Research on Rural Planning Teaching Reform under the Background of National Spatial Planning (grant number: J20230180).

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to concerns regarding the privacy of individual participants and the sensitive nature of the research data. All requests for data will be subject to an ethical review process to ensure that the privacy of participants is maintained and that the use of data is in line with ethical guidelines for research.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Expert Scoring Sample Form.

Importance Score	Very Important	Important	Neutral	Unimportant	Very Unimportant
	5	4	3	2	1
Building roof damage degree					
Building feature damage degree					
Building function change rate					
Building dimension contradiction rate					
Building structural damage degree					
Damage degree of courtyard form					
Street scale damage degree					
Street coordination					
Street continuity					
Enclosing boundary survivability					
Fabric evolution degree					
Note					

Appendix B

Table A2. Calculation Method and Connotation of Indicators.

Index Classification	Element Attributes	Index Name	Index Definition	Symbolic Representation and Calculation Method	Index Annotation
Static index	Buildings (Node)	Building roof damage degree	The degree of damage to the roof of a building	$RF = \sum_{i=1}^{3} N_{Ri}/N_A \cdot w_i$	N_{Ri} is the number of roofs with different degrees of damage, N_A is the total number of roofs within the plot, w_i is the weight of roofs with different degrees of damage.
		Building structural damage degree	The proportion of the number of buildings with structural damage to the total number of buildings	$S_d = N_{SD}/N_A$	N_{SD} is the total number of build-ings with structural damage within the plot, N_A is the total number of roofs within the plot.
		Building feature damage degree	Weighted summation of the proportion of the land area of buildings with different styles and features to the total building area of the entire plot	$AP = \sum_{i=1}^{5} S_{Pi}/S_A \cdot w_i$	$S_{Pi}$is the base area of buildings with different features, S_A is the total base area of buildings within the plot, w_i is the weight of buildings with different styles and features.
		Building function change rate	The proportion of buildings with changed functions to the total number of buildings	$F_c = N_{FC}/N_A$	N_{FC} is the total number of build-ings with functional chang-es within the plot, N_A is the total number of buildings within the plot.
		Building dimension contradiction rate	The proportion of uncoordinated building area in total building area	$V_d = S_{VD}/S_A$	S_{VD} is the total area of the build-ing base with inconsistent volume, S_A is the total base area of buildings within the plot.
	Courtyard (Node)	Damage degree of courtyard form	The proportion of different degrees of collapsed courtyards to the total number of courtyards	$YD = \sum_{i=1}^{5} N_{Yi}/N_{AY} \cdot w_i$	N_{Yi} is the number of damaged courtyards in category i, N_{AY} is the total number of court-yards, w_i is the weight of courtyards with different degrees of damage.
	Street system (Path)	Street scale damage degree	Absolute value of the difference between the width to height ratio of main streets and historical street standard values	$LS = \lvert D_i/H_i - R_S \rvert$	D_i/H_i is the aspect ratio of the main streets and alleys in the i-th plot, R_S is the standard aspect ratio of historical streets and alleys.
		Street coordination	The coordination degree of the main street and alley facades in terms of style and appearance	$C_{di} = \{1, 2, 3, 4, 5\}$	C_{di} is the coordination degree of the facade style of the main streets and alleys in the i-th plot
		Street continuity	Main Street thread adhesion rate	$TAR = L/\sum S_i \cdot K_i$	S_i is the projected length of the legal setback line of the i-th building on the red line of the streets and alleys; K_i is the minimum legal dis-tance between the red lines of the streets and alleys in the i-th building; L is the length of the centerline of the street and alley.
	Boundary (Edge)	Enclosing boundary survivability	Comparing historical data, the remains of authentic city walls, green belts, rivers, and other surrounding boundaries in the block	$B_{si} = \{1, 2, 3, 4, 5\}$	B_{si} is the remaining situation of the i-th plot's enclosing boundary.
Dynamic index	Evolution (District)	Architectural evolution degree	Compare the historical buildings of the plot in historical data, overlap them with the current historical buildings, and determine the degree of preservation of the historical buildings	$AE = \sum_i^n S_{ANi}/\sum_j^m S_{APj}$	S_{ANi} is the current building base area within the plot; S_{APj} is the base area of historical buildings within the plot.
		Evolution degree of streets	Compare the road network system of the plot in historical data, overlap it with the current road network, and determine the degree of preservation of the historical road network	$SE = \sum_i^n S_{Ni}/\sum_j^m S_{Pj}$	S_{Ni} is the current area of streets and alleys within the plot; S_{Pj} is the area of past streets and alleys within the plot.
		Fabric evolution degree	The sum of architectural evolution and street evolution	$TE = \lvert AE - 1 \rvert + \lvert SE - 1 \rvert$	AE is the degree of architectural evolution; SE is the degree of evolution of streets.

Appendix C

Table A3. Data Collection Sample Table.

Total Courtyard Quantity		
Total building quantity		
Fabric evolution	Street evolution	
	Building evolution	
Enclosing boundary survivability	Score	
Street continuity	Score	
Street coordination	Score	
Street scale	Score	
Courtyard form	Score	
	Weight	1
	0/4	
	Weight	3
	1/4	
	Weight	5
	2/4	
	Weight	7
	3/4	
	Weight	9
	4/4	
Building volume	Score	
Building function	Score	
Building feature	Score	
	Weight	1
	Poor	
	Weight	3
	Fair	
	Weight	5
	Average	
	Weight	7
	Good	
	Weight	9
	Excellent	
Building structure	Score	
Building roof	Score	
	Weight	3
	Proportion of dilapidated roofs	
	Weight	6
	Proportion of intact roofs in residential buildings	
	Weight	9
	Proportion of intact ancient building roofs	

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