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Prediction of Deterioration Level of Heritage Buildings Using a Logistic Regression Model

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Abstract: Chinese historical and cultural villages are known for numerous vernacular architectural heritages of a wide-ranging, widely distributed, and artificially intensive nature. In order to efficiently and rapidly conduct targeted conservation for heritage buildings, the prediction of the deterioration level of heritage buildings is a key prerequisite. In that respect, it is of the utmost importance to investigate the influence of different elements, such as the age and type of heritage building, on the deterioration of heritage buildings. This paper presents the feasibility of using logistic regression models to establish a heritage damage prediction and thereby confirm the buildings' deterioration level. The model results show that age, type, style, and value play important roles in predicting the deterioration level of heritage buildings. Meanwhile, the correlation between the judging factors of heritage buildings and the deterioration level of the damage has also been revealed, which is expected to support subsequent conservation and restoration.

Keywords: logistic regression analysis; heritage buildings; deterioration level assessment; prediction model

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Citation: Chen, S.; Chen, J.; Yu, J.; Wang, T.; Xu, J. Prediction of Deterioration Level of Heritage Buildings Using a Logistic Regression Model. *Buildings* **2023**, *13*, 1006. https://doi.org/10.3390/buildings13041006

Academic Editor: Antonio Formisano

Received: 12 March 2023
Revised: 1 April 2023
Accepted: 3 April 2023
Published: 11 April 2023

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1. Introduction

China is well-known for its abundant cultural heritage, in which immovable historical buildings are highly valued as relics of great historical, cultural, and artistic value [1]. By the end of 2011, a total of 766,722 immovable cultural relics were surveyed and registered in China, including 193,282 ancient cultural sites, 139,458 ancient tombs, 263,885 ancient buildings, 24,422 cave temples and stone carvings, 14,449 modern important historical sites and representative buildings, and 4226 other categories. Among them, Zhejiang Province registered a total of 73,943 immovable cultural relics (3773 ancient sites, 37 ancient tombs, 3554 ancient tombs, 46,214 ancient buildings, 914 cave temples and stone carvings, modern important historical sites, and representative buildings, and 19,278, 210 others). Informative data, including the total amount, distribution, type, age, ownership, use, human environment, natural environment, protection level, protection status, and destruction factors, were collected in the census. Meanwhile, a number of new cultural heritage types, such as industrial heritage, vernacular architecture, 20th century heritage, and cultural landscape, were registered. More importantly, this census has revealed that the deterioration in the vernacular architectural heritage is complex, and the large difference in the degree of deterioration significantly hinders the effective protection of cultural heritage [2].

The sustainable development of heritage buildings directly relies on their maintenance status. For example, the deterioration of heritage buildings has an adverse effect on their

conservation due to negligent management. Presently, about one-fourth of the immovable cultural relics are in an inferior state of conservation. However, the on-site survey of cultural relic buildings varies from region to region, leading to increased complexity [3]. Suboptimal management not only endangers the sustainability of heritage buildings, but also poses impediments in protection, especially for historical and cultural villages that possess a large number of sub-provincial cultural relic building-protection units, but of a low grade. For example, it is scarcely feasible to protect most of the historical and cultural villages located in the mountainous hills of Zhejiang Province due to inconvenient access for traffic Such a case results in the high cost of the site survey of the heritage buildings in terms of the inefficiency of walking surveys and the difficulty of deterioration monitoring. Furthermore, a preliminary survey revealed that the overall historical features of most villages are relatively well preserved, yet the main surfaces and structures of the cultural relics have suffered serious deterioration. Problems such as peeling off of buildings' wall finishes and salt crystals on the surface of walls due to the wet environment have aggravated the situation. Wooden buildings are seriously decayed, with partial roof collapses and tile fragmentations becoming more and more serious, such as the traditional residential houses in Hutang Street and LiZhu Town, Shaoxing City (Figure 1). The number of immovable cultural relics that are facing these situations in China is huge, and the serious state of heritage deterioration requires some simple and convenient methods for effective probing.

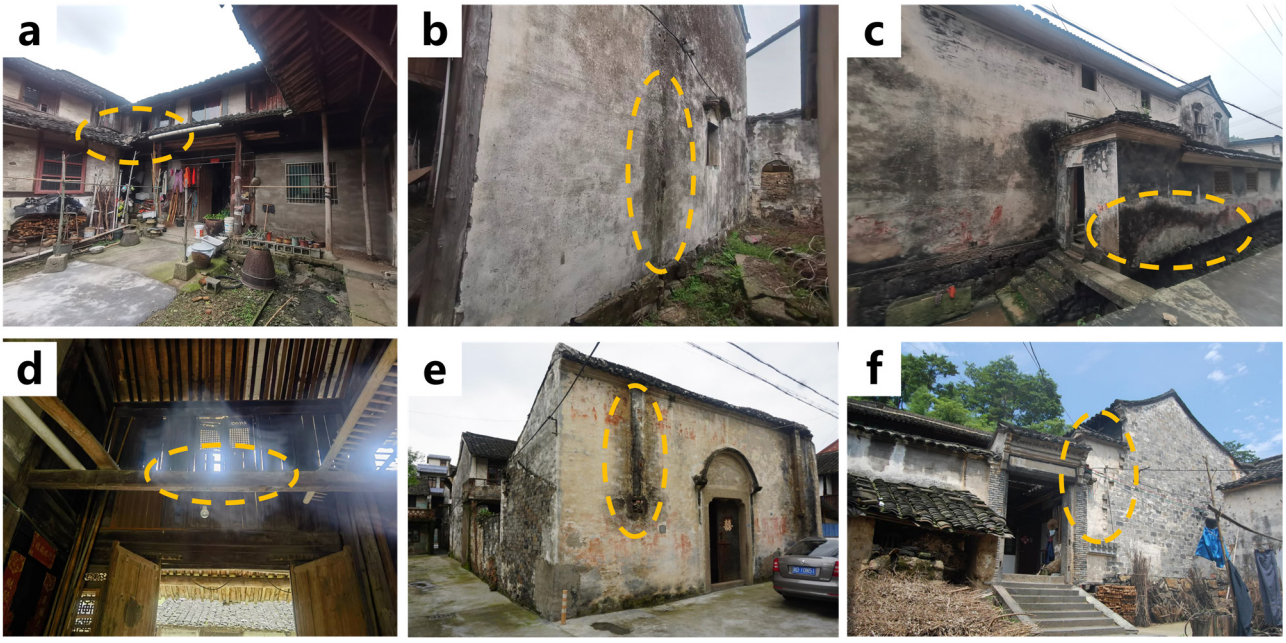


Figure 1. Buildings: (**a**–**c**) Shaoxing City Keqiao District LiZhu town residential; (**d**–**f**) Shaoxing City Keqiao District Hutang street residential. Yellow circles present deterioration areas.

Presently, the conventional methods for the protection of heritage buildings include using state-of-the-art geodesy and terrestrial laser scanning (TLS) [4]. Geometric changes are examined, identified, and documented using regression analysis methods, revealing changes and distortions related to map scale [5–8]. The preliminary investigation workload is huge, which is not suitable for building complexes [9,10]. Some studies utilize the environment temperature and humidity to predict the damage caused by freeze–thaw cycles in cold regions [11–13]. Meanwhile, there are also studies using methods such as decision trees to establish prediction functions to estimate the depth of the structural decay of wood in historic buildings [14]. In addition, deep learning methods are introduced to classify post-disaster building damage and help in post-disaster reconstruction [15–22]. Probabilistic Bayesian methods and digital photogrammetry data were applied to determine the deterioration pattern and rate of deterioration of brick walls, and non-destructive testing methods were used to assess the structure of historic

buildings [23–29]. The results offer reliable data for architects to formulate conservation plans and ensure the safety of heritage buildings. These building conservation methods still require a lot of upfront survey work, involving detailed and complicated experimental testing work. Such labor-intensive tests are not applicable to the large-scale screening of the deterioration of historic buildings.

A valuable heritage census can be fully utilized to contribute to heritage conservation. For example, the prediction of building deterioration by the logistic regression model is a good topic for exploration. The image analysis of heritage building deterioration needs to be modularized and systematic, and the national heritage census information resources can be fully utilized with the help of logistic regression analysis [30–33]. For example, the collection of elemental information, such as building age, building type, building value, building style, and deterioration characterization, is increasingly combined with the use of logistic regression analysis to achieve the prediction of deterioration levels and the extensive screening of heritage buildings. However, this combination based on logistic regression analysis is less utilized in the field of architectural heritage deterioration analysis. Therefore, this study has great research value and significance. The analysis and application of predictive models for deterioration have not yet been explored. Less attention normally results in poor protection. Therefore, more efforts should be devoted to seeking available protection techniques, in order to implement a full investigation and compressive analysis of heritage information for heritage buildings.

Zhejiang Province embraces a long history and rich heritage composition, therefore there is a strong need for a heritage damage investigation and prediction assessment to achieve the sustainable development of heritage. Research on the prediction model of the heritage building deterioration of historical and cultural villages becomes more urgent. In this work, we prioritized surveying 120 heritage buildings in 14 historical and cultural villages in Shaoxing, which is a city in Zhejiang Province. The influence of different factors such as age and type of heritage building on the deterioration of heritage buildings was studied using a logistic regression model to predict the deterioration level of heritage buildings. After the repeated training and model testing of the assessment data, the correlation between the judging factors of the heritage buildings and the deterioration grade of the damage is explored. This work is expected to promote the in-depth study of data and visualization of the deterioration of heritage buildings and provides a scientific reference basis for the subsequent conservation and restoration of architectural heritage. In addition, the discovery of heritage deterioration prevention strategies that can be effectively predicted and implemented provides the necessary basic data for the subsequent management of architectural heritage deterioration.

2. Methodology

2.1. Target Sample

In total, 120 immovable cultural relics in 14 villages and towns in Shaoxing City, Zhejiang Province, were selected and several evaluation factors, such as GPS coordinates, building age, building type, usage, restoration, willingness to protect, historical and cultural value, architectural style, building quality, and building area, were set as the model training indexes according to the census registration forms provided by local cultural relics protection departments. Regional variability indexes were screened, and the building age, building type, historical and cultural value, building style, and features were finally determined as the evaluation indexes of the building deterioration level. A qualitative analysis of building deterioration levels and generation patterns was performed through prediction by logistic regression models and the application of fuzzy theory. The correlation between the type, age, value, historical style, and features of heritage buildings and building deterioration was studied to predict the deterioration level.

2.2. Logistic Regression Analysis

Logistic regression analysis is specifically used for providing solutions for regression problems in which the response variable is a discrete attribute variable, and the independent variable is a continuous variable or a discrete attribute variable. The general logistic regression model is only applicable to binary variables such as "yes, no", but in the prediction of the deterioration level condition, the deterioration level is divided into I, II, III, and IV in order to obtain more accurate and specific results. The logistic regression model is a very effective method for this multivariate analysis problem.

For the dichotomous problem, regression modeling can be performed directly using the logistic function, where the logistic function expression is:

$$Logistic(t) = \frac{1}{1+e^{-t}} \tag{1}$$

Dichotomous logistic regression model:

$$y_1 = P(y=1|X) = Logistic(w^T X + b) = \frac{1}{1+e^{-(w^T X+b)}} \tag{2}$$

$$y_0 = P(y=0|X) = 1 - P(y=1|X) \tag{3}$$

where y_1, y_0 are the model probabilities when the dependent variables are 1 and 0, respectively; X is the independent variable; w is the regression slope vector; and b is the parameter.

For the multivariate classification problem, the general form is the logistic function softmax function, with the following expressions:

$$Softmax(t_i) = \frac{e^{t_i}}{\sum_{j}^{K} e^{t_j}} \tag{4}$$

For the K classification problem, the logistic regression model has the following form:

$$y_i = P(y=i|X) = Softmax(w_i^T X + b) = \frac{e^{w_i^T X+b}}{\sum_{j}^{K} e^{w_j^T X+b}}, i = 1,2,3, \cdots, K \tag{5}$$

where y_i is the model probability when the y dependent variable is i, i with $1,2,3,\cdots,K$, K values; X is the independent variable; w is the regression slope vector; and b is the regression intercept vector.

The model probabilities of a sample are obtained at the 1st, 2nd, 3rd ... K levels of model probability, and then i is selected, when the model probability achieves the maximum value, as the prediction level of the sample.

3. Results and Discussion

3.1. Evaluation Factor

In this study, Python and Numpy, Pandas, and Scikit-learn data processing libraries were chosen for model training and prediction. The model was built using 120 groups of historical buildings in Zhejiang Province as samples after processing. The original data contain four evaluation indicators, namely X1: building age, X2: building category, X3: historical value, X4: architectural style, and the dependent variable deterioration level Y.

Building age is a discrete ordered variable, from the Ming Dynasty, Ming/Qing Dynasty, Qing Dynasty, Qing Dynasty/Republic of China, Republic of China, Republic of China/Post-Construction (50s–80s), Post-Construction (50s–80s), to Post-Construction (after 80s), with the model assigning values of 1,2,3..., from ancient to modern. The building category contains three types of buildings: public buildings, industrial buildings and

annexes, and residential buildings. X3: historical value and X4: architectural style are discrete ordered variables encoded with natural numbers, and A, B, C, and D are assigned as 1, 2, 3, and 4, respectively. There are four values in the original data of the grade: 'light', 'lighter', 'heavy', and 'heavier'. The deterioration levels are also discrete ordered variables, so "Especially serious", "Very serious", and "Generally serious" are coded as 1, 2, and 3, in that order. However, there is only one building with a 'heavy' deterioration level, so it is coded as 3 to improve the accuracy of the model.

3.2. Interpretation of Evaluation Factor

3.2.1. Building Age and Type

"Cultural heritage" can be understood as evidence of the possession of cultural values, which are intended to transcend administrative traditions based on monumental buildings or landscapes that are essentially associated with shared aesthetic values. According to the national regulations on the approval of the national key cultural relics protection units, the determination of the title of the research object, and the classification of the grade, the cultural heritage buildings in the historical and cultural villages of Shaoxing City, Zhejiang Province, are set according to the parameters of the construction era and the type of architecture [34–37]. These buildings were mainly built in China during the Ming Dynasty, Qing Dynasty, and the Republic of China and after the founding of the country (1950s–80s). The building types include residential buildings (such as ancient ruins and former residences of famous people), public buildings (such as commercial, cultural, temples, post halls, and schools), industrial buildings (such as factory buildings), and structures (such as bridges, ancient towpaths, and pagodas).

3.2.2. Historical Value of Heritage Buildings

The two reports on the World Heritage List released by ICOMOS in 2004 and 2008 not only established a complete system of value analysis and assessment, but also reinterpreted the meaning of "highlighting universal values" and emphasized that the purpose is to base everything on heritage values. Heritage buildings not only carry historical information, but are also important physical evidence of science, technology, and social development. Therefore, heritage buildings become an important physical carrier of cultural heritage and have historical value [28,38–41].

Article 3 of Chapter 1 of the Law of the People's Republic of China on the Protection of Cultural Relics states that "immovable cultural relics such as ancient cultural sites, ancient tombs, ancient buildings, cave temples, stone carvings, murals, important historical sites and representative buildings of modern times, according to their historical, artistic, and scientific value, can be identified as national key cultural relics protection units, provincial cultural relics protection units, and municipal and county cultural relics protection units." This shows that the value of the high and low judgment determines the level of protection of the cultural relic's protection units [42–44]. The hierarchical differences of different cultural heritage buildings also form the value hierarchy [13]. The difference in value determines the difference in the grade of heritage buildings, and the grade determines the measures of protection and governance (Figure 2). Therefore, the immovable cultural relics selected for the article mainly involve national key cultural relics' protection units, provincial cultural relics' protection units, municipal cultural relics' protection units, and general immovable cultural relics, which are set to four grades of A/B/C/D, respectively, according to the value of the grade evaluation.

3.2.3. Historical Style and Features

In order to evaluate the heritage value of historical and cultural villages, the evaluation factors are set according to the conservation principles of historical and cultural villages, and the statistics are evaluated in three aspects: the historical characteristics of buildings, the systematicity of architectural symbols, and the integration of architectural colors. The historical features can be integrated from three elements, such as the roof,

windows, doors and walls, etc., and the standard score is calculated as three points, with three elements surviving intact as excellent (three points), two elements surviving intact as good (two points), one element surviving intact as medium (one point), and none of the three elements surviving as poor (zero points). In addition, the scores are divided into 0–3 according to the degree of systemic architectural symbols and the degree of color integration, and finally, all the scores are summed and averaged, and the final evaluation grade is rounded off [45–48].

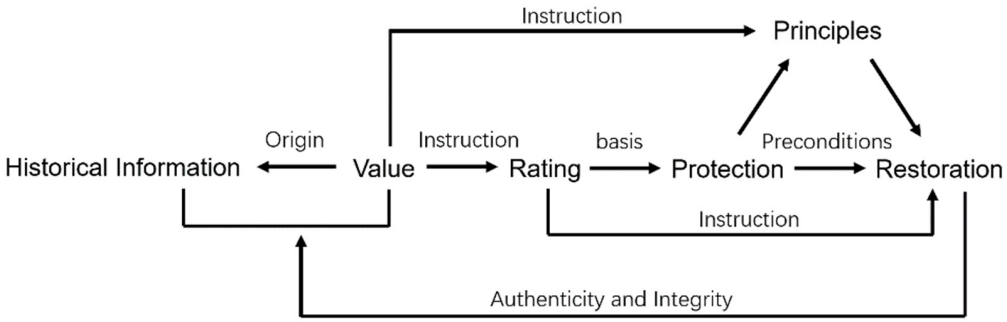


Figure 2. The value of heritage buildings and the level of protection.

Taking the Han family residence in Siqiao village, Ma'an town, Shaoxing city, as an example, among the historical features of the building, the characteristic elements of the roof and windows and doors survive relatively intact, while the historical features of the wall elements have disappeared; therefore, the evaluation grade is good (actual score 2), the symbolic system of the building is relatively complete, the evaluation grade is excellent (actual score 3), the color integration of the building is relatively good, and the evaluation grade is good (actual score 2). The average score is 2.333, about 2 points, and the overall evaluation grade is B (Table 1).

Table 1. Historic landscape evaluation assessment of Han family residence in Siqiao village.

Parameters	Poor	Medium	Good	Excellent	Standard	Actual Rating
Historical features (roofing, windows, doors, wall)	0	1	2	3	3	2
Architecture symbolic system	0	1	2	3	3	3
Color integration	0	1	2	3	3	2
Comprehensive rating		——			3	2.333 ≈ 2

3.2.4. Deterioration Level

According to the division of the project quality assessment levels in China's construction projects, the sub-items, divisions, and unit works are assessed as qualified and excellent levels according to the national standards, and the assessment levels are divided into five levels corresponding to five score rates, which are level 1 (100%), level 2 (90%), level 3 (80%), level 4 (70%) and the lowest level 5 (0%). In addition, standard scores are set for different items and the corresponding score rates are derived, thus achieving a comprehensive rating of the building. Based on this, this paper takes the perceptual quality parameters of the state of damage of heritage buildings as the deterioration level assessment standard and divides the damage of heritage buildings into four levels, which are especially serious (level 1), very serious (level 2), generally serious (level 3), and slightly serious (level 4); as heritage buildings have experienced long years of baptism and have certain chronological characteristics, there is no situation that is absolutely free of damage, so there is no minimum level 5.

According to the principle of deterioration of heritage buildings, there are several forms of building deterioration. Salt crystallization is mainly reflected in the surface of the wall weathering, masonry internal moisture in the soluble salt with the evaporation of

water, and precipitation and crystallization on the surface of the masonry. The weathering phenomenon is mainly manifested as the surface of the masonry block being eroded by the wind, after which the surface is in a powder state, block corners are rounded, and mortar texture is loose, intensifying moisture erosion. The phenomenon of layer cracking is mainly reflected in the bulging of the stucco layer, in the form of small crocodile skin-shaped pile-up cracks, which evolve into layer separation or even spalling as the damage increases. Disintegration is the cracking of the block as a whole and is a more in-depth form of damage than layer cracking [44–46]. In such circumstances, the unit block microstructure might reach the limit of resistance and decompose, resulting in the phenomenon of block crumbling or, even worse, leading to structural cracks in the wall, endangering the stability and safety of the masonry structure. (Table 2).

Table 2. Building deterioration level assessment classification.

Deterioration Level		**Especially Serious (Level 1)**	**Very Serious (Level 2)**	**Generally Serious (Level 3)**	**Slightly Serious (Level 4)**
Deterioration types	Alkali crystals	The surface layer of the stucco layer is peeling off, the mechanical properties of the block surface layer are weakened, and the structural members are exposed	The matrix is brittle, crumbly, or powder-like, adhering to the surface, and gradually deteriorating to the interior	Soluble salts are precipitated with the evaporation of water, and white crystals are attached to the masonry surface	The wall humidity increases and shows local color darkening and a water line and other moisture phenomena
	Chalking	Chalking depth of block surface > 2 cm	Chalking depth of block surface > 1.5 cm	Chalking depth of block surface $\leq$ 1 cm	Chalking depth of block surface $\leq$ 0.5 cm
	Bulging	Cracking and partial peeling of the surface layer of stucco	Surface stucco cracking	Surface stucco cracking, into small cracks	The surface layer of stucco, slightly hollow drum, no cracking phenomenon
	Disintegration	Large area of block disintegration and falling off	Crumbling in smaller pieces	No significant disintegration	The surface of the wall is basically intact
	Cracks	Structural exposed corrosion, through cracks in walls	The block has obvious cracks, the gray joints fall off but do not form through joints	The block is basically intact, the gray joints appear to fall off seriously and form gaps	Ash joints partially pulverized, no obvious shedding, no coherent joints formed
Appearing site		Bottom of the wall	Middle of the wall	Corner, cornice	Cornice, sill
Structural layer		Structural layer corrosion Exposure of structural layer brick wall	Plaster priming layer Surface coating layer Brick wall	Plaster priming layer Surface coating layer	Plaster priming layer Surface coating layer
Illustrations					

3.3. Accuracy Test of the Model

The Scikit-learn library was used to divide 80% of the dataset into a training set and 20% into a test set, using the training dataset for model training and the test set for model testing (Figure 3). A total of 7 out of 24 samples in the test set were found to be wrong, and the correct sample prediction rate was 70.83%, indicating that the model has a strong prediction ability. The model parameters and the detailed results of the model predictions are shown in Tables 3 and 4.

```
from sklearn.model_selection import train_test_split
from sklearn.linear_model import LogisticRegression
✓ 0.3s

X_train, X_test, y_train, y_test = train_test_split(data_X, data_y, test_size=0.2)
model = LogisticRegression(random_state=random_state,max_iter=max_iter,penalty=penalty,solver=solver)
model.fit(X_train, y_train)
print('Accuracy_score')
print(model.score(X_test,y_test))
print('Coefficient')
print(model.coef_)
✓ 0.6s

Accuracy_score
0.7083333333333334
Coefficient
[[-0.29784764 -0.63331148  0.91668175 -0.28406979 -0.63201078 -1.06174506]
 [ 0.09650216  0.20649972 -0.09685723 -0.1096427  -0.02986741  0.26802613]
 [ 0.20134548  0.42681176 -0.81982452  0.39371249  0.66187819  0.79371892]]
```

Figure 3. Screenshot of the code of logistic regression algorithm.

Table 3. Logistic regression analysis of multi-categorical dependent variables of deterioration level.

No.	Evaluation Factor						Model Prediction				Actual Deterioration Level
	X1	X2_1	X2_2	X2_3	X3	X4	y_1	y_2	y_3	Deterioration Level	
1	1	1	0	0	2	2	0.26	0.58	0.16	2	2
2 *	4	1	0	0	1	1	0.46	0.49	0.05	2	1
3	3	0	0	1	3	3	0.02	0.39	0.58	3	3
4 *	3	1	0	0	1	1	0.56	0.4	0.04	1	2
5	3	1	0	0	2	2	0.13	0.65	0.22	2	2
6 *	3	1	0	0	1	2	0.24	0.65	0.11	2	3
7	8	0	0	0	1	1	0.28	0.63	0.08	2	2
8	3	1	0	0	1	1	0.56	0.4	0.04	1	1
9	3	0	0	1	1	2	0.37	0.52	0.11	2	2
10	3	0	1	0	2	3	0.22	0.64	0.14	2	2
11	1	0	1	0	1	1	0.95	0.05	0	1	1
12 *	3	0	1	0	2	2	0.53	0.41	0.05	1	2
13	5	1	0	0	2	2	0.06	0.67	0.27	2	2
14 *	3	0	0	1	3	3	0.02	0.39	0.58	3	1
15	3	0	0	1	1	2	0.37	0.52	0.11	2	2
16 *	1	0	0	1	1	3	0.24	0.58	0.18	2	3
17	3	1	0	0	1	1	0.56	0.4	0.04	1	1
18*	5	0	0	1	1	1	0.52	0.42	0.07	1	2
19	3	0	0	1	2	2	0.22	0.55	0.24	2	2
20	3	1	0	0	3	2	0.06	0.56	0.37	2	2
21	3	0	0	1	1	2	0.37	0.52	0.11	2	2
22	3	0	0	1	3	3	0.02	0.39	0.58	3	3
23	7	1	0	0	4	3	0	0.23	0.77	3	3
24	3	1	0	0	1	2	0.24	0.65	0.11	2	2

* indicates wrong sample.

Table 4. Model parameters.

y	X1	X2_1	X2_2	X2_3	X3	X4
1	−0.298	−0.633	0.917	−0.284	−0.632	−1.062
2	0.097	0.206	−0.097	−0.11	−0.03	0.268
3	0.201	0.427	−0.82	0.394	0.662	0.794

Among the six independent variables, X1, X2_1, X2_2, X2_3, X3, and X4, the three regression coefficients of each independent variable show monotonicity. X1 shows monotonic increasing, showing a more recent deterioration possibility of historical buildings, thus indicating that the older the historical buildings are after the Ming and Qing dynasties, the more valuable they are for conservation and the less deteriorated they are. X2_1, X2_2, and X2_3 show monotonic increasing and X2_1 and X2_3 show monotonic decreasing. X2_2 is monotonically increasing and X2_1 and X2_3 are monotonically decreasing, indicating that 'industrial buildings and appurtenances' have deteriorated more than 'public buildings' and 'residential buildings'. The degree of deterioration is higher. The 'industrial buildings and appurtenances' are used mainly for practical purposes and have a relatively low conservation value. Parameters X3 and X4 both show a monotonic increasing trend, suggesting that the degree of deterioration is lower when 'historic value' 'architectural style' is coded as 1 (i.e., rated as A). It implies that buildings with a higher historical value architectural style present a trend of a lower deterioration level. This may be due to the higher likelihood that historic buildings with a higher conservation value will be repaired in the near future, and thus their deterioration level rating is lower. The independent variables X2_2 and X4 model parameters have the largest extreme differences, indicating that the two indicators of building category and building style have a greater influence on predicting the deterioration level of buildings. Therefore, judging from the status quo of architectural heritage, it can be reflected that there will be great differences in the types of buildings with different functions, and the integrity of historical features will also lead to different treatment. Additionally, for cultural relic buildings, the difference in deterioration will be more obvious.

4. Conclusions

In this study, we use a logistic regression model to deal with collected census data, such as the age and type of heritage buildings, in order to establish an efficient assessment of the deterioration of heritage buildings. The prediction of building deterioration levels is identified by using a heritage deterioration prediction model. The correlation between the judging factors and the deterioration level of the heritage buildings is explored. The two indicators of building type and architectural style have the greatest influence in predicting the deterioration level of buildings. Other factors including the age, type, historical value, and architectural style of the building have a more significant role in the deterioration of heritage buildings, compared with geographic location, temperature, humidity, and topography. Specifically, the older the heritage building is, the lower the deterioration degree will be. Meanwhile, compared to the "public buildings" and "residential" type of heritage building, the "industrial buildings" type of heritage building suffers from more serious deterioration.

Establishing a deterioration prediction using a logistic regression model is feasible. However, it still has some limitations. In the process of the census of heritage buildings, the census takers who have different theoretical perceptions probably cause fluctuations in judging factors. We can continue to explore the assessment of deterioration of heritage buildings in historical and cultural villages on a national scale. A similar approach can also be applied to the study of assessing the deterioration mechanism of heritage buildings. More variables such as authenticity, integrity, and outstanding universal value can be explored in the modelling, and our data may present more valid results in future studies.

Author Contributions: Conceptualization, S.C. and T.W.; methodology, S.C. and T.W.; software, J.X. and J.Y.; formal analysis, J.C. and J.Y.; writing—original draft preparation, S.C. and J.Y.; writing—review and editing, S.C. and J.Y.; funding acquisition, S.C., T.W. and J.X. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the National Natural Science Foundation of China (Nos. 52102369, 52208057), Natural Science Foundation of Zhejiang Province (Nos. LQ21E080012, LQ20E080021), Ministry of Education humanities social sciences research project (No. 20YJC760101), Zhejiang cultural relics protection science and technology project (No. 2021017), and Guangdong Provincial Natural Science Foundation—General Project (No. 2023A1515011191).

Data Availability Statement: Data are unavailable due to privacy.

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

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