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A Decision-Making Method for Bridge Network Maintenance Based on Disease Transmission and NSGA-II

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Abstract: Due to the unreasonable allocation method, the bridge maintenance funds in Shaanxi Province can not provide maximum value. In this study, we used different functions to fit the actual technical condition data of bridges in Shaanxi in recent years, and through comparison, the exponential model with the best fitting effect was selected as the deterioration model for the bridge and its parts. Based on this, the deterioration characteristics of the bridge and its parts were further analyzed. Based on the results of the analysis, the deterioration coefficients (A) applicable to the bridge and its parts in Shaanxi Province, considering the ages and service environments of the bridges, are summarized. The concept of disease transmission is proposed based on the different deterioration characteristics of the bridge parts. The deck pavement, expansion joints, and bearings were identified as the key components of disease transmission, and the disease transmission paths were built with them as the center. Considering the technical benefits, economic benefits, and diseases of the key components of bridge maintenance, the second-generation nondominated sorting genetic algorithm (NSGA-II) was used to calculate the maintenance fund allocation scheme in the bridge network maintenance decision under different budget–demand ratios. The findings show that there are significant differences in the deterioration rates of the deck systems, superstructures, and substructures, as well as of the overall bridges, in Northern Shaanxi, Central Shaanxi (Guanzhong region), and Southern Shaanxi. Diseases of the bridge deck pavement, expansion joints, and bearings can lead to diseases of other elements. Compared with the traditional method of allocating maintenance funds based on the principle of prioritizing bridges with the worst technical conditions, the economic condition growth rates of the results of this study were 94.2%, 106.2%, 92.9%, and 62.8% for budget–demand ratios of 20%, 40%, 60%, and 80% of the maintenance funds, respectively. The proposed method for allocating bridge maintenance funds provides a reference for the subsequent development of bridge maintenance decision specifications.

Keywords: bridge engineering; bridge network maintenance; deterioration model; disease transmission; NSGA-II; budget–demand ratio

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1. Introduction

Over the past few decades, China has built a large amount of transportation infrastructure to support its rapid economic and social development, including hundreds of thousands of highway bridges. Nowadays, due to the relatively poor design standards of these bridges and increasing traffic loads, a large number of them are unable to perform their normal functions [1]. It is foreseeable that a large number of bridges in China will reach their service lives at the same time in the near future and enter a period of concentrated maintenance and reinforcement. With limited maintenance resources, large-scale bridge maintenance is bound to have a huge impact on road traffic and economic development. Against this background, the scientific formulation of bridge maintenance strategies in the network to make full use of maintenance funds and extend the service lives of bridges has become an important task for the maintenance of highway bridges in China.

Bridge deterioration characteristics are important bases for formulating maintenance strategies. Existing studies have investigated the overall deterioration patterns of bridges, such as segment linear and nonlinear deterioration models [2], cluster analysis models [3], and deterioration models under human intervention and after unexpected events [4]. However, there has been no research focus on the deterioration of bridge superstructures, substructures, or deck systems according to the actual inspection data of multiple bridges. The links between bridge component diseases are not explored deeply enough, and most studies focus on the impact of individual component diseases on the bridge and their countermeasures, such as bearing disengaging [5,6], the deterioration of the bridge deck [7], reinforcement corrosion [8], and hinge-joint damage [9,10]. Some scholars are aware of the interactions between the various bridge components [11]; however, the relationship between the different component diseases has not yet been systematically investigated.

In existing studies [12–16], the decision indicators considered in bridge network maintenance strategies are the bridge's physical condition and age, the type of structure, the maintenance cost, the user satisfaction, and its importance in the bridge network. To consider the influence of various indicators on the maintenance strategy, various decision-making methods have been used in existing studies, such as: the genetic algorithm [12]; system classification and statistical analysis [17]; data envelopment analysis [18]; Lagrange decomposition [19]; the analytic hierarchy process [20]; the multitiered prioritizing method [21]; the expert evaluation method [22]; the nuclear space cloud model method [23]; the group-ordering method [24]; the integer-programming method [25]; the ALAPR principle [26]; and the particle swarm optimization algorithm [27]. The bridge network maintenance decision has been studied by scholars, and many results have been achieved; however, there are also shortcomings. Firstly, most of the studies are based on the overall technical condition of the bridge and do not consider the difference in the impact on the overall bridge structure due to the occurrences of diseases in different components. Secondly, the existing studies have not considered the impact of different maintenance funds on maintenance decisions, which often leads to the unreasonable allocation of funds and a low return on the maintenance investment, and which cannot truly achieve scientific decision making for bridge maintenance.

Therefore, in this study, we used the actual technical conditions of the highway bridges in Shaanxi Province to fit the deterioration models of the bridges and their components, and we identified the deck pavement, expansion joints, and bearings as the key components for disease transmission according to the relationship between the diseases of the bridge components. A three-dimensional multiobjective decision optimization function was developed based on the maintenance costs, economic benefits (considering the impact of the key component diseases), and technical benefits. A model for reasonable decision making and the allocation of maintenance funds for bridge network maintenance was established under different budget–demand ratios, and the NSGA-II was used to achieve the multiobjective optimization of bridge maintenance decisions.

2. Bridge Deterioration Models

2.1. Bridge Condition Data and Processing Method

According to the Standards for Technical Condition Evaluation of Highway Bridges (JTG/T H21-2011) [28], when the bridge is new and fully functional, the technical condition score is [95,100] and the technical condition class is 1; when the bridge has minor defects that do not affect the use function, the score is [80,95) and the class is 2; when the bridge has moderate defects but is still able to maintain normal use function, the score is [60,80) and the class is 3; When the main components of the bridge have large defects that seriously affect the bridge function or load-bearing capacity and cannot guarantee normal use, the score is [40,60) and the class is 4; when the main components of the bridge have serious defects and cannot be used normally, endangering the safety of the bridge and putting the bridge in a dangerous state, the score is [0,40) and the class is 5. The technical conditions of nearly 20,000 concrete girder bridges in various regions of Shaanxi Province were assessed using this method. Scatter diagrams were drawn and are presented in Figure 1.

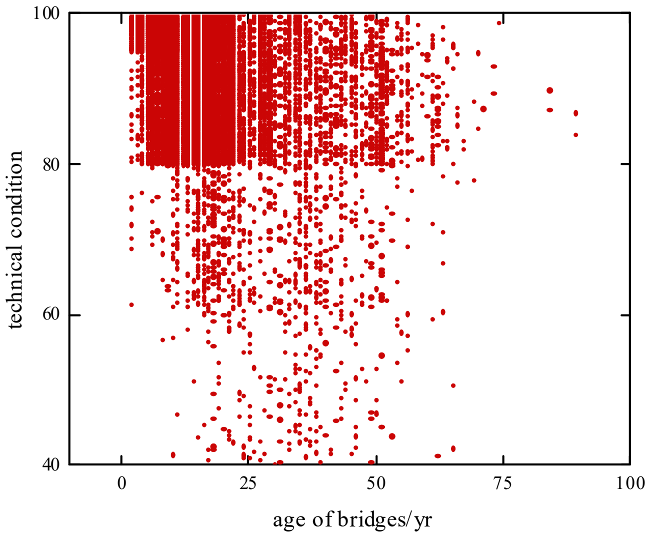


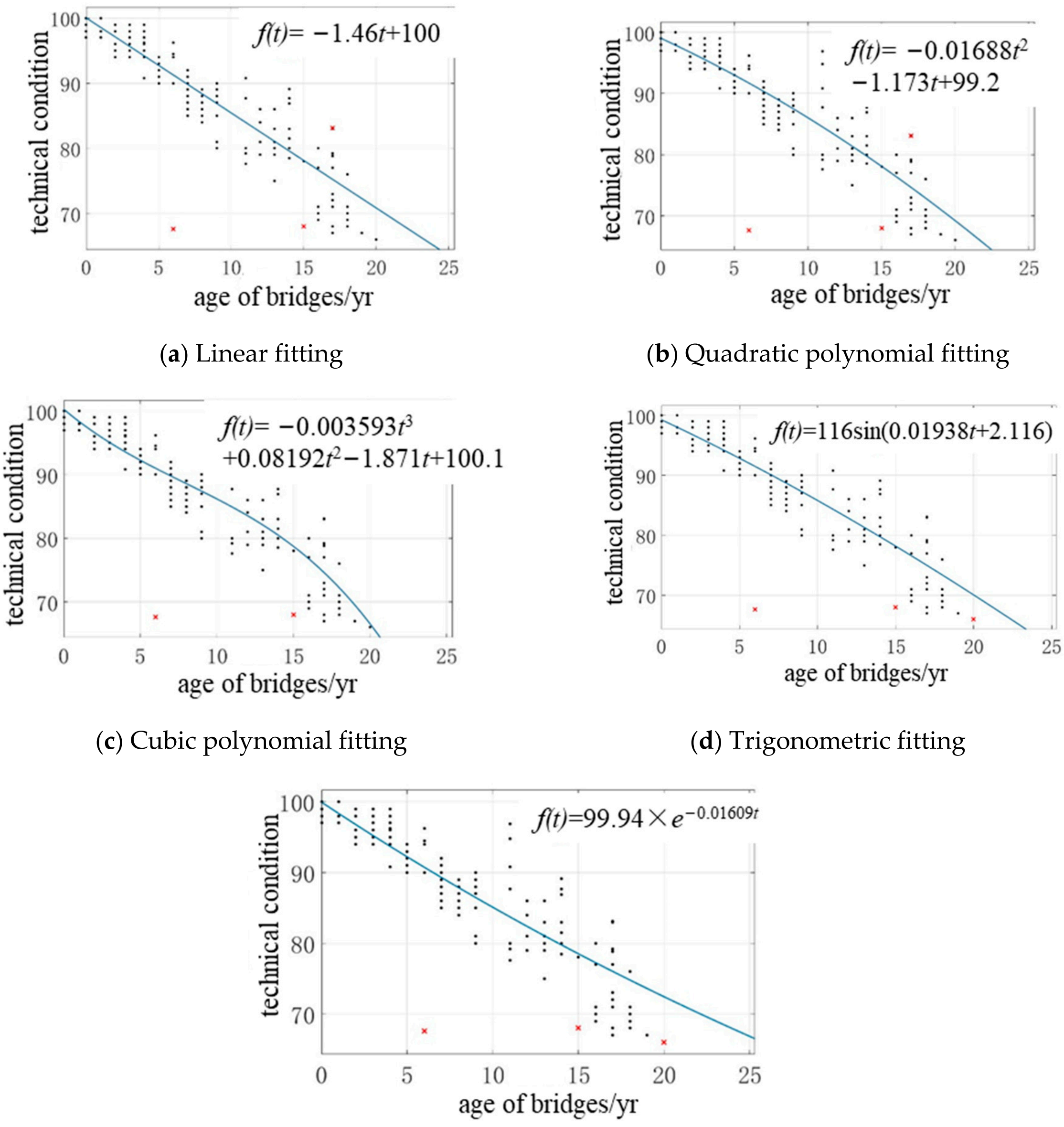
Figure 1. Scatter plot of ages and technical conditions of bridges.

As bridge deterioration is influenced by multiple factors, such as the bridge's structure type and age, the traffic load, environmental factors, and maintenance, bridge technical condition data are discrete, and especially for older bridges that have been maintained and repaired several times cannot accurately reflect the deterioration characteristics of the bridge structure in its natural state. In this section, a simply supported slab bridge with a span of 8 m and a load rating of highway class I [29] is used as the object. The technical condition score of the bridge is used as the performance deterioration index, and the deterioration curve of each part of the bridge structure is obtained using mathematical regression analysis. The information from the successive bridge inspection and maintenance history can be used as a data basis for predicting the deterioration of the technical conditions of bridges. Considering the uncertainty of the data, it is necessary to process them in advance, as follows:

(a) During service, bridges are inevitably maintained and repaired. Bridges that have taken reinforcement or renovation are considered newly built bridges, and their ages are recorded as 0. For example, the technical condition score is 75 when the bridge is 29 years old, and the score is 94 after maintenance or reinforcement when the bridge is 30 years old. The age is corrected to 0 from 30 years;
(b) Assume that the bridge deteriorates gradually and that the technical condition score cannot be higher in the latter than in the former. If the latter is higher than the former, the relevant data are excluded;
(c) The data should be evenly distributed across the various bridge ages. If there is a period of a lack of data, then the relevant bridge technical condition data can be supplemented by calculating the transition probability matrix for the first two bridge ages and using Markov chain prediction methods;
(d) Considering that the process of assessing the technical conditions of bridges is influenced by the subjective factors of the inspectors and there is a certain amount of error, it is assumed that the technical conditions of bridges of the same bridge type, span, and age obey a normal distribution. Then, the abnormal values can be removed according to the PauTa criterion [30].

2.2. Deterioration in Different Parts of Bridge

Bridges consist of three parts: the deck system (including deck pavement, drainage system, expansion joints, and parapets), superstructure (including main girders and bearings), and substructure (including piers, piles, and foundations) [28]. A total of five fitting functions (linear, quadratic polynomial, cubic polynomial, trigonometric, and exponential) were used to fit the technical condition scores of 108 bridges. The fitted curves for the deck system are shown in Figure 2.



(**a**) Linear fitting (**b**) Quadratic polynomial fitting

(**c**) Cubic polynomial fitting (**d**) Trigonometric fitting

(**e**) Exponential fitting

Notation: × are the points to be discarded in the fitting due to excessive deviations, similarly hereinafter.

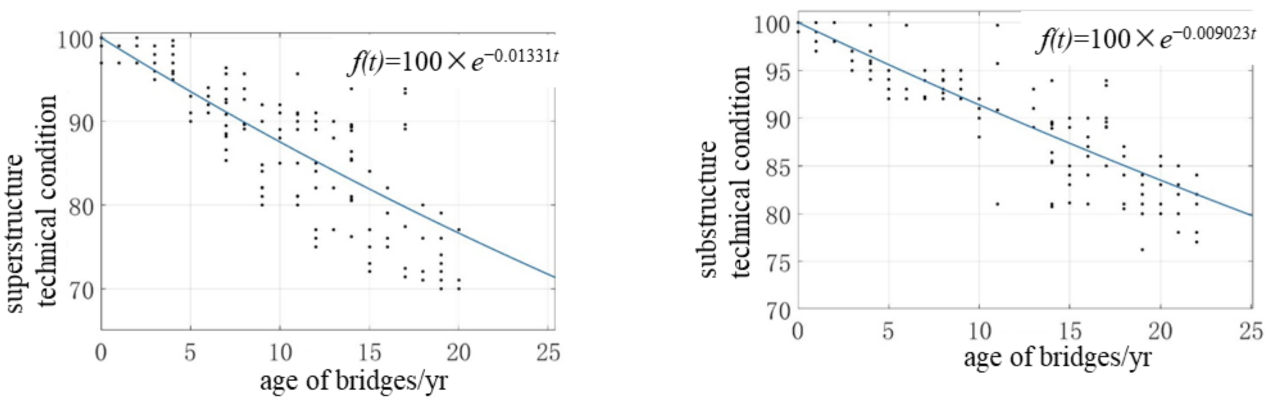
Figure 2. Deterioration model of bridge deck.

The evaluating indicators for the regression models are shown in Table 1. Among the five models, the exponential model had the smallest error sum of squares (2813), and its square of the correlation coefficient was close to 0.8. Thus, the exponential model fit best among the five models.

Table 1. Fitting parameters.

Type of Fit Function	Error Sum of Squares	Mean Square Error	Square of Correlation Coefficient
Linear	2956	4.052	0.8049
Quadratic polynomial	2948	4.036	0.8140
Cubic polynomial	2898	4.012	0.8171
Trigonometric	2950	4.037	0.8138
Exponential	2813	3.964	0.8019

According to the above method, the superstructure and substructure technical condition data are processed by the exponential fitting method to obtain their deterioration models, as shown in Figure 3.



(**a**) Superstructure (**b**) Substructure

Figure 3. Deterioration models of superstructure and substructure.

Figure 4 shows the deterioration curves of various parts. The deterioration rate of the deck system is the fastest, followed by the superstructure and substructure, and it is close to the existing results [31]. The deck system deteriorates from 100 points (in good condition) to 60 points (boundary of class 3 and 4) in 32 years, the superstructure in 38 years, and the substructure in 56 years. The deterioration rate of the deck system is approximately 1.2 times that of the superstructure, and 1.8 times that of the substructure. Therefore, sufficient attention should be given to the deck system during bridge maintenance.

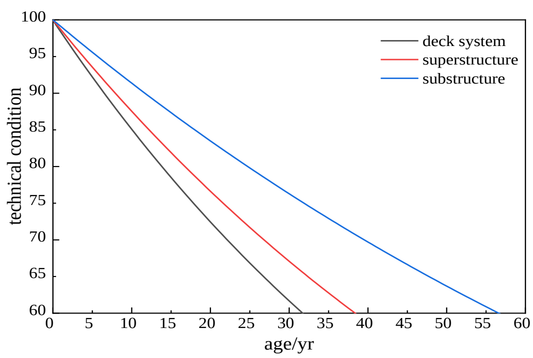


Figure 4. Deterioration curves of various parts of bridge.

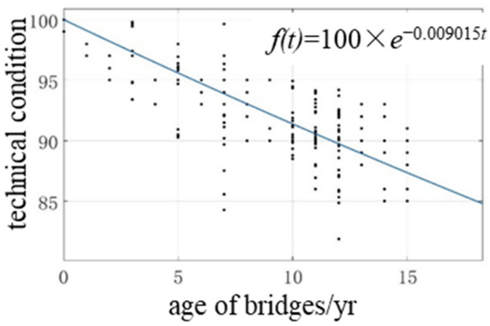
According to the exponential function, the general form of the exponential deterioration model can be obtained by the following:

$$f(t) = C_0 e^{-At} \quad (1)$$

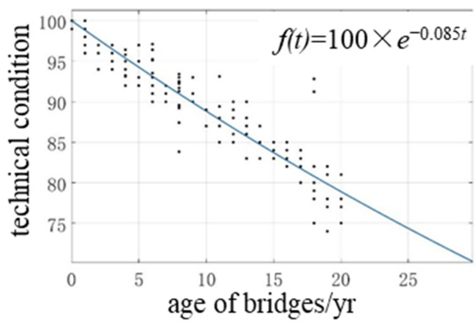
where $f(t)$ is the technical condition score, t is the bridge age, and A is the deterioration coefficient. The larger the absolute value of A, the faster the deterioration of the structure.

2.3. Deterioration in Different Regions of Shaanxi Province

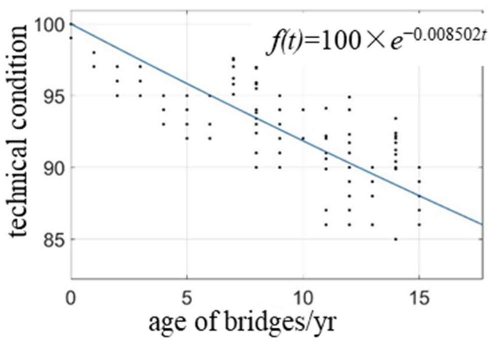
The different regions of Shaanxi Province have different natural geological conditions and climatic environments, as well as wide differences in economic development, which has resulted in the strong geographical characters of the service environments of the bridges. This section analyzes the deterioration rates of voided slab bridges in three regions: Northern Shaanxi, Central Shaanxi (the Guanzhong area), and Southern Shaanxi, as shown in Figure 5. A comparison of the bridge deterioration rates in each region is shown in Figure 6.



(**a**) Northern Shaanxi



(**b**) Guanzhong



(**c**) Southern Shaanxi

Figure 5. Deterioration models in different regions of Shaanxi Province.

In Figure 6, the deterioration rates of the bridges in each region show significant geographical differences, with the fastest deterioration in Guanzhong, followed by Northern Shaanxi, and the slowest in Southern Shaanxi. The deterioration coefficients (A) of the bridges in each region are shown in Table 2. These were consistent with the degree of regional economic development in Shaanxi Province. The economy of Guanzhong is more developed than those of Northern and Southern Shaanxi, with higher traffic volumes and bridge utilization rates. Therefore, the bridges in Guanzhong have larger deterioration coefficients.

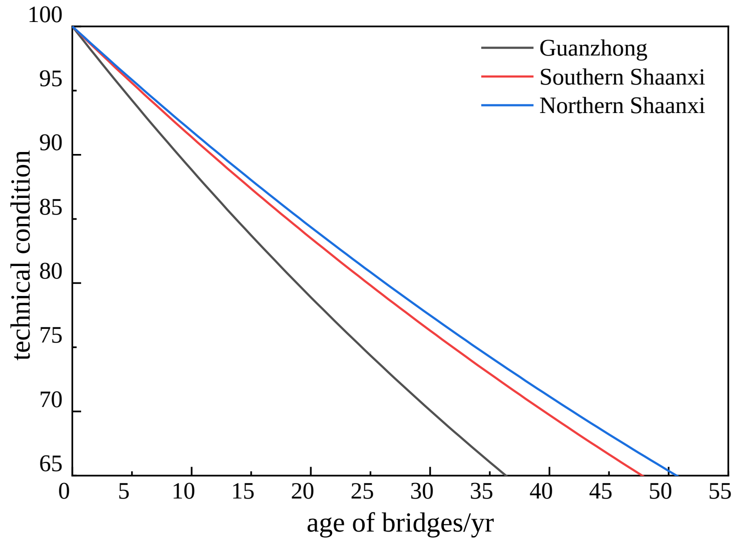


Figure 6. Comparison of regional deterioration rates.

Table 2. Deterioration coefficients for bridges in three regions.

Region	Northern Shaanxi	Guanzhong	Southern Shaanxi
Deterioration coefficient (A)	9.015×10^{-3}	11.850×10^{-3}	8.502×10^{-3}

2.4. Influencing Factors on Deterioration Coefficients (A)

Bridge deterioration is a complex process with many uncertainties, and it is mainly influenced by the materials, environment, and loads. The material is an intrinsic factor in determining the structural deterioration. Different materials have different deterioration rates and are affected by the environment differently. For example, concrete and steel have decidedly different deterioration characteristics. The temperature, humidity, and load of the service environment are the external factors of bridge deterioration, and the coupling effect of the load, temperature, and humidity exacerbates the deterioration and leads to different rates of deterioration for each part of the bridge. The deck, for example, is directly exposed to the environment and is affected by the temperature, humidity, and live loads, which result in rapid deterioration. The superstructure and substructure are protected by the deck and are therefore less affected by the service environment. In terms of the overall bridge deterioration rates, the rate in Guanzhong is higher than those in Northern and Southern Shaanxi due to the high traffic volume and complex service environment.

Therefore, a generic model for bridge deterioration should be able to reflect the effects of the materials, the service environment, and other influencing factors, and it can be simplified as follows:

$$C(t) = C_0 e^{-\xi 1 \xi 2 \alpha t} \tag{2}$$

where $C(t)$ indicates the technical condition of the bridge in the age of t; C_0 is the initial technical condition, which is generally taken as 100; ξ_1 is the influencing factor of the service environment, which is determined according to the natural environment (temperature, humidity, sunlight, wind, etc.) and live loads; ξ_2 is the influencing factor of the material, determined according to the difference in the deterioration characteristics of steel, concrete, wood, etc., with concrete as the benchmark with a value of 1.0 (few cases of steel and wooden bridges are found in Shaanxi, and so they are not discussed); and α is the generic annual deterioration rate related only to the structure itself.

By corresponding the deterioration models for each part of the bridge developed in Section 2.2 and the bridge deterioration models in each region developed in Section 2.3 to the coefficients in Equation (2), the relevant coefficients for each deterioration model were obtained, as shown in Table 3. The component deterioration model is based on the superstructure, with $\alpha = 13.3 \times 10^{-3}$. The values of ξ_1 are 1.39, 1, and 0.67 for the deck system, superstructure, and substructure, respectively. The bridge deterioration model is based on Southern Shaanxi, with $\alpha = 8.5 \times 10^{-3}$. The values of ξ_1 are 1.06, 1.39, and 1 for Northern Shaanxi, Guanzhong, and Southern Shaanxi, respectively. It can be seen that the generic deterioration model of Equation (2) applies to each bridge component and the bridge as a whole in each region of Shaanxi Province.

Table 3. Coefficients for each deterioration model.

Model Type	Component/Region	C_0	ξ_1	ξ_2	α
Component deterioration models	Deck system	100	1.39	1	13.3×10^{-3}
	Superstructure		1		
	Substructure		0.67		
Bridge deterioration models	Northern Shaanxi		1.06		8.5×10^{-3}
	Guanzhong		1.39		
	Southern Shaanxi		1		

The values of the service environmental influencing factor (ξ_1) vary considerably between the structures of the bridges, with the value of ξ_1 for the deck system approximately twice that for the substructure. The reason for this is that the deck system is the protective layer for both the superstructure and substructure and is directly exposed to environmental effects, such as rain and snow and the impact of vehicles; therefore, the deck system is most affected by the service environment. The bridge deck system is subjected to environmental effects, which are transferred to the superstructure and substructure through the deck pavement, bearings, and expansion joints, causing feedback from the superstructure and substructure to the environmental effects, and leading to structural diseases in severe cases. In summary, the bridge is subjected to environmental effects in a top-down process. A similar process may also exist in the generation of bridge diseases. This hypothesis is tested below through the study of bridge disease development patterns.

3. Bridge Disease Transmission

3.1. Bridge Disease Transmission Concept

A bridge is a whole structure that is composed of different elements, which are interlinked and interact with each other. The deterioration and damage processes of the bridge elements also interact with each other and are manifested at the disease level, where a disease in one element may trigger a disease in another element. In this section, this phenomenon is referred to as bridge disease transmission.

During the bridge service, each member is subject to deterioration and disease due to the repeated effects of traffic loads and the continuous erosion of the natural environment. Some elements' diseases do not affect the other elements, while some elements' diseases can cause the diseases of other members or promote the development of diseases through the disease transmission effect. These members are defined as the key members for disease transmission in this paper. The following section analyzes three aspects: the deck pavement, expansion joints, and bearings.

3.2. Deck Pavement

Figure 7 shows the transmission path of deck pavement diseases. Design defects, construction defects, and other factors lead to initial defects in the pavement upon the completion of construction, and the pavement has premature cracking and deterioration during service due to repeated vehicle loads and a lack of regular maintenance and repair [32,33]. The deck ponding carries chloride ions that are left behind by de-icing salts, which seep into the girders and wet joints from the pavement cracks and result in chloride salt erosion. Under the effect of chloride erosion, the bonds between the joints decrease, and the longitudinal shear transfer capacity between the slabs is greatly reduced, which results in the transformation of the overall slab bearing into an in-plane combined-slab bearing, or even the phenomenon of "single slab force", which eventually leads to structural safety problems [34,35].

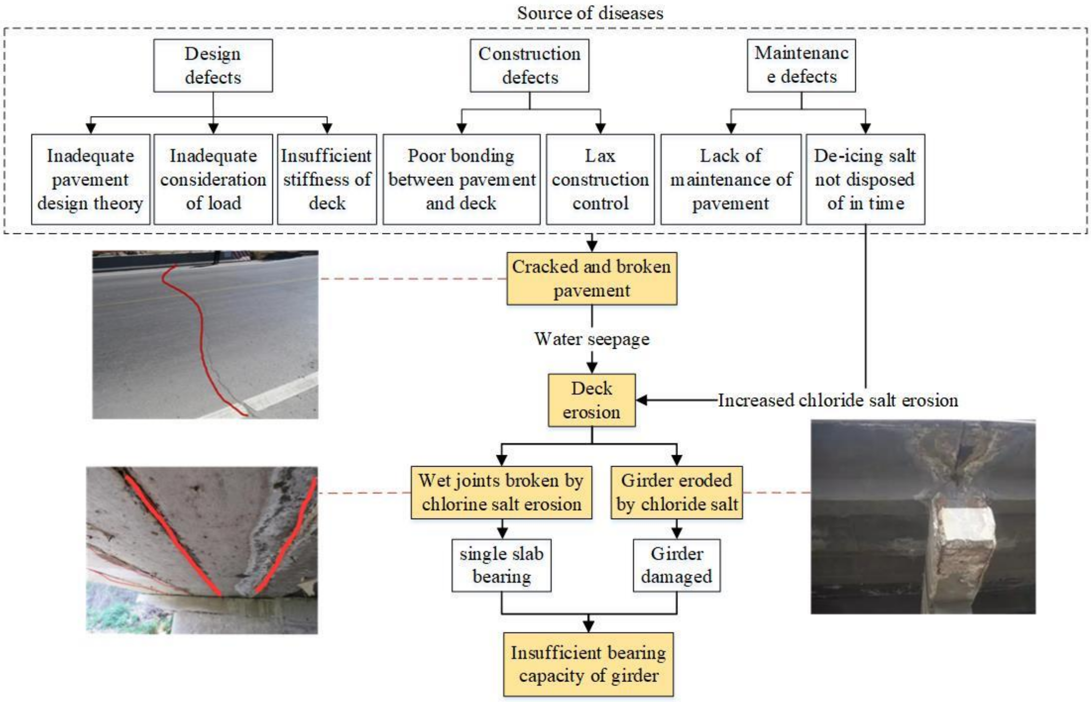


Figure 7. Disease transmission paths of deck pavement.

3.3. Expansion Joint

Figure 8 shows the transmission paths of expansion-joint diseases. When the expansion joint is blocked, a huge negative bending moment is generated at the end of the beam during the high-temperature period, which results in the restraining of the deformation of the deck near the expansion joint and the crushing of and damage to the slab, which eventually cause cracking at the end of the anchorage area of the expansion joint. The blockage of the expansion joint also leads to the crushing of the girder and the back of the abutment, which can even cause the end of the girder and abutment to break and crack [36]. When the expansion-joint rubber strips fall off, the bridge deck wastewater and debris flow down the expansion joint, which leads to the aging and cracking of the bearing, the rusting of the steel plate, and the accumulation of the bearing rubbish. This limits the sliding deformation of the bearing and causes additional internal forces in the main beam. The wastewater flowing down the expansion joint also leads to the concrete carbonization and reinforcement corrosion of the piers and abutments [37].

3.4. Bearing

Figure 9 shows the transmission paths of bearing diseases. In the case of voided slabs, the bearing vacancy can lead to increased forces on the pavement and hinge joints, which can easily lead to the longitudinal cracking of the pavement and the dislodging of the hinge joints under repeated vehicle loads, which eventually leads to single-slab force. When the bearing is vacant, the main beam becomes less constrained and a larger torsion of the beam occurs, which, in turn, leads to the twisting and deformation of the expansion joint, which exacerbate its unevenness and seriously affect its normal function. Under vehicle load and temperature effects, the abnormal bearing slippage leads to the restricted deformation of the main beam, which generates additional stress.

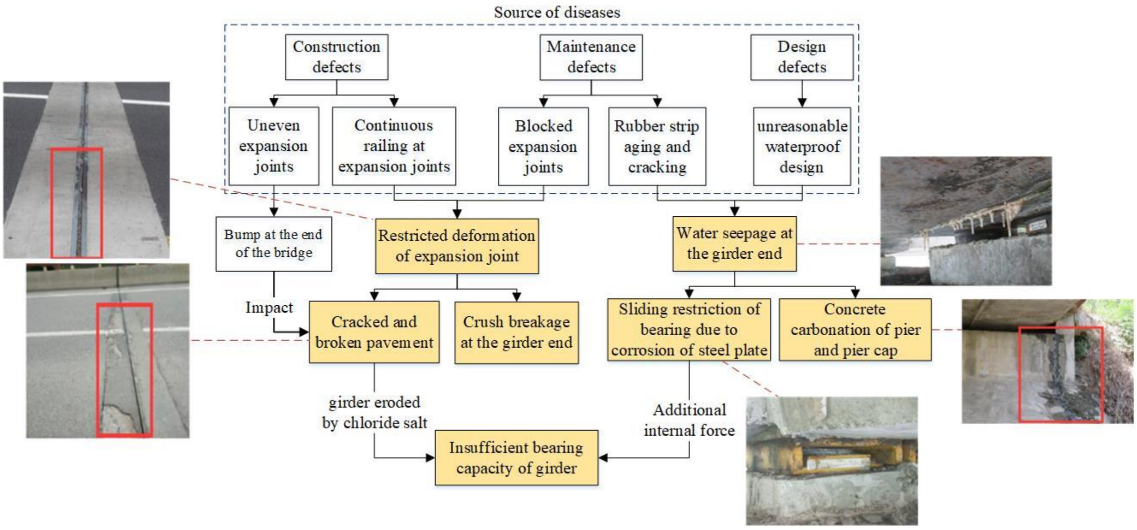


Figure 8. Disease transmission paths of expansion joints.

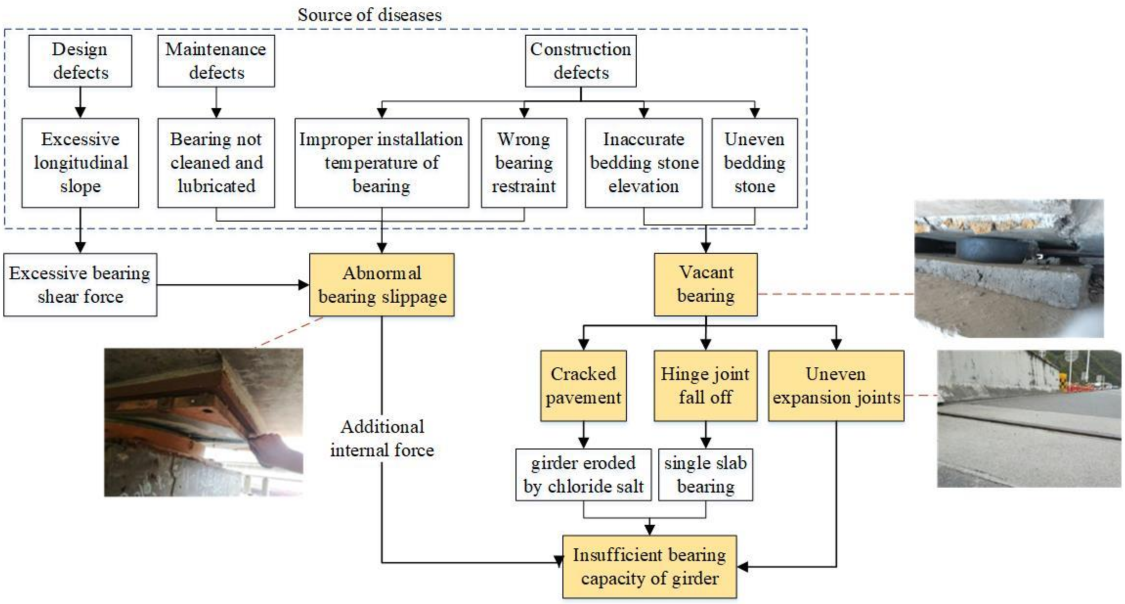


Figure 9. Disease transmission paths of bearings.

In bridge maintenance, the pavement, expansion joints, and bearings should be given timely and proactive maintenance, and the diseases on the disease transmission paths should be focused on. To stop the development of a disease along the transmission path, the deterioration of the elements should be slowed down and the durability of the bridge improved.

4. A Multiobjective Maintenance Decision Method for the Bridge Network Based on NSGA-II

4.1. Current Situation of Allocation of Bridge Maintenance Funds

A summary of the allocation of maintenance funds in the past five years by a municipal road bureau in Shaanxi Province is shown in Figure 10. Routine maintenance and minor repairs account for a small proportion of the maintenance funds (about 18%), and medium and major repairs account for a large proportion (about 80%). The highway bridges have prematurely entered a period of high disease incidence due to the use of passive corrective maintenance, which, in turn, has led to the allocation of the limited maintenance funds to medium and major repairs. This results in an unreasonable allocation of maintenance funds, which, in turn, inevitably compresses the maintenance funds for routine maintenance and minor repairs, which further exacerbates the corrective maintenance model and the low return on investment of the bridge maintenance funds.

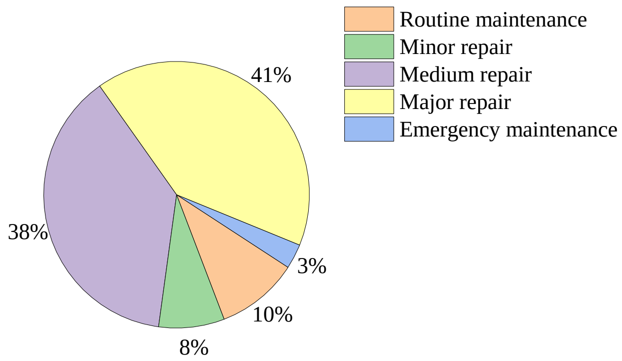


Figure 10. Allocation of funds for bridge maintenance by the highway bureau of Shaanxi (from 2015 to 2020).

Based on this situation, it is necessary to develop a reasonable allocation method for bridge maintenance funds to achieve optimal performances, minimum capital investment, and maximum maintenance benefits during the service lives of bridges.

4.2. Maintenance Decision Considerations and Their Quantification

The traditional bridge network maintenance decision only considers the technical condition of the bridge and does not fully consider the economic benefits that it introduces. This decision-making approach has resulted in a low return on bridge maintenance funds. In this paper, the bridge network maintenance decision considers three factors, as shown in Table 4.

Table 4. Key considerations for bridge network maintenance decisions.

Key Considerations	Technical Benefits of Maintenance	Economic Benefits of Maintenance	Maintenance Costs
Quantification methods	Value of increased technical condition of bridges as a result of maintenance	Value of increased truck commodity flow as a result of maintenance [38]	Budget Quota for Highway Bridge Maintenance Engineering (JTG/T 5612-2020) [39]

4.3. Multiobjective Optimization Model for Maintenance Decision

The bridge network maintenance decision is based on the selection of the priority bridges for maintenance among the bridges with maintenance needs based on the actual situation. When dealing with practical maintenance decisions, the maintenance objectives often conflict with each other. To make scientific and rational maintenance decisions, it is necessary to solve the multiobjective optimization problem among the funds, technical benefits, and economic benefits.

We translated the multiobjective optimization problems for maintenance decisions into a mathematical model. There are n maintenance decision objectives, each with a different constraint. The optimization model is as follows:

$$\begin{aligned}&\mathrm{Min}\, f(X)\\&X=\{x_1,x_2,\ldots,x_n\},\ x_i\in D_i\\&D_i=\{d_{i1},d_{i2},d_{i3},\ldots,d_{im}\},\ i=1,2,\ldots,n\\&g_k(x)\le 0,\ k=1,2,\ldots,N_c\end{aligned} \tag{3}$$

where $f(X)$ is the decision objective function; $g_k(x)$ is the decision constraint function; X is the n-dimensional decision vector; i is the decision variable; D_i is the i-th decision solution set; d_{im} is the allowed value of the i-th decision variable; m is the number of feasible solutions; N_c is the number of constraint objectives.

Multiobjective optimization ultimately results in a Pareto solution set, which allows decisionmakers to make scientific and rational decisions and select suitable solutions according to the actual needs and available maintenance funds.

4.4. Principle of NSGA-II

The main steps of the NSGA-II [40] include coding, population initialization, the calculation of the objective function, etc., as shown in Figure 11.

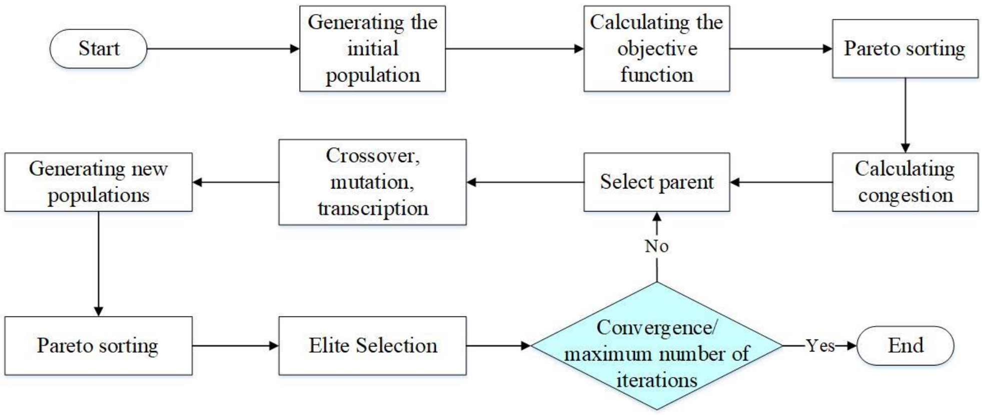


Figure 11. NSGA-II flow.

5. Case Studies

5.1. Case Data

A maintenance management department in Shaanxi Province has 20 bridges with maintenance needs within its jurisdiction, as shown in Figure 12. In the maintenance decision for the bridges with more serious defects of the key components of the disease transmission, the economic benefit of maintenance is increased by 20% based on the original (i.e., the economic benefit coefficient is 1.2). The technical condition and economic and technical benefits of maintenance, as well as the maintenance cost of each bridge, are specified in Table 5.

Figure 12. Distribution of 20 bridges.

Table 5. Information for bridge maintenance decisions.

Bridge Number	Technical Condition before Maintenance (Score)	Technical Benefits of Maintenance (Score)	Economic Benefits of Maintenance (CNY 10^3)	Is the Key Component Defective?	Revised Value of Economic Benefits of Maintenance (CNY 10^3)	Maintenance Costs (CNY 10^3)
1	75	10	1000	No	1000	290
2	72	12	300	No	300	150
3	69	13	1800	No	1800	340
4	84	5	1100	Yes	1320	90
5	79	10	1500	No	1500	90
6	67	20	1900	No	1900	300
7	87	3	2300	No	2300	80
8	76	9	3100	No	3100	80
9	65	25	2800	Yes	3360	300
10	64	22	1200	No	1200	290
11	63	25	2100	Yes	2520	350
12	62	20	2100	No	2100	160
13	61	23	4300	No	4300	340
14	78	14	3400	No	3400	200
15	77	11	2500	Yes	3000	170
16	76	10	1600	Yes	1920	100
17	75	20	700	No	700	400
18	74	15	700	No	700	450
19	85	5	1500	No	1500	80
20	89	5	1200	No	1200	70
Total	1478	277	37,100	/	39,120	4330

Notation 1: Bridges numbered 4, 9, 11, 15, and 16 have defective key components. Notation 2: The technical benefit is the improvement value of the technical condition of the bridge after maintenance. Taking Bridge 1 as an example, the technical condition of the bridge before maintenance is 75, and that after maintenance is 85; thus, the technical benefit of the maintenance for this bridge is 10. The technical benefit values in this case were provided by the bridge maintenance experts of the Department of Transport of Shaanxi Province. Notation 3: The economic benefit of maintenance is related to the importance of the bridge in the road network. The higher the importance of a bridge in the road network, the greater the maintenance economic benefits. The economic benefit values in this case were provided by the bridge maintenance experts of the Department of Transport of Shaanxi Province.

5.2. Maintenance Decision Optimization Function Construction

This section establishes the optimization function of the bridge network maintenance decision to maximize the economic and technical benefits and minimize the maintenance costs. The constraint is the available maintenance funds (C) of the maintenance agency. Thus, the multiobjective optimization model can be expressed as follows:

Objective 1: maximum total economic benefits of bridge maintenance:

$$Maxf_1(x) = \sum_{j=1}^{n} v_j x_j \tag{4}$$

Objective 2: maximum total technical benefits of bridge maintenance:

$$Maxf_2(x) = \sum_{j=1}^{n} l_j x_j \tag{5}$$

Objective 3: minimum total maintenance costs:

$$Ming(x) = \sum_{j=1}^{n} c_j x_j \tag{6}$$

Constraint function: total maintenance costs not greater than C:

$$g(x) = \sum_{j=1}^{n} c_j x_j \leq C,\ x_j = 0\text{or}1,\ j = 1, 2 \ldots, n \tag{7}$$

where j denotes the bridge number (j = 1, 2, . . . , n); n denotes the total number of bridges in the region with maintenance needs; C denotes the total cost of the bridge maintenance that can be used by the maintenance agency; c_j denotes the maintenance cost of bridge j; l_j denotes the maintenance technical benefit value of bridge j; v_j denotes the maintenance economic benefit value of bridge j; and X_j denotes the decision variable for bridge j: $X_j = 1$ if bridge j is maintained, and $X_j = 0$ otherwise.

5.3. Analysis of Optimization Results

This section analyzes the bridge maintenance sequencing method and reasonable allocation method of funds when the budget–demand ratio of the maintenance funds is 20%, 40%, 60%, and 80%. According to Table 5, the total bridge maintenance fund demand is CNY 4.33 million. The multiobjective optimization problem of bridge maintenance is solved using the NSGA-II, and the set of Pareto solutions is obtained as shown in Figure 13.

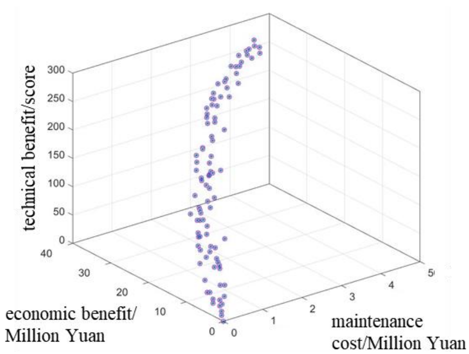


Figure 13. Pareto solutions of multiobjective maintenance decision.

The set of Pareto solutions with a budget–demand ratio of 20% (i.e., CNY 866,000 in maintenance funds) is shown in Figure 14a, and the economic benefits, technical benefits, and maintenance funds for each maintenance option are shown in Table 6. In total, there are six bridge network maintenance options, all with a maintenance fund of CNY 860,000, of which the highest economic benefit option is Option 6, with a total economic benefit of CNY 17.32 million, and the highest technical benefit option is Option 1, with a total technical benefit of 81. The bridge maintenance management can choose a reasonable maintenance option according to the maintenance focus.

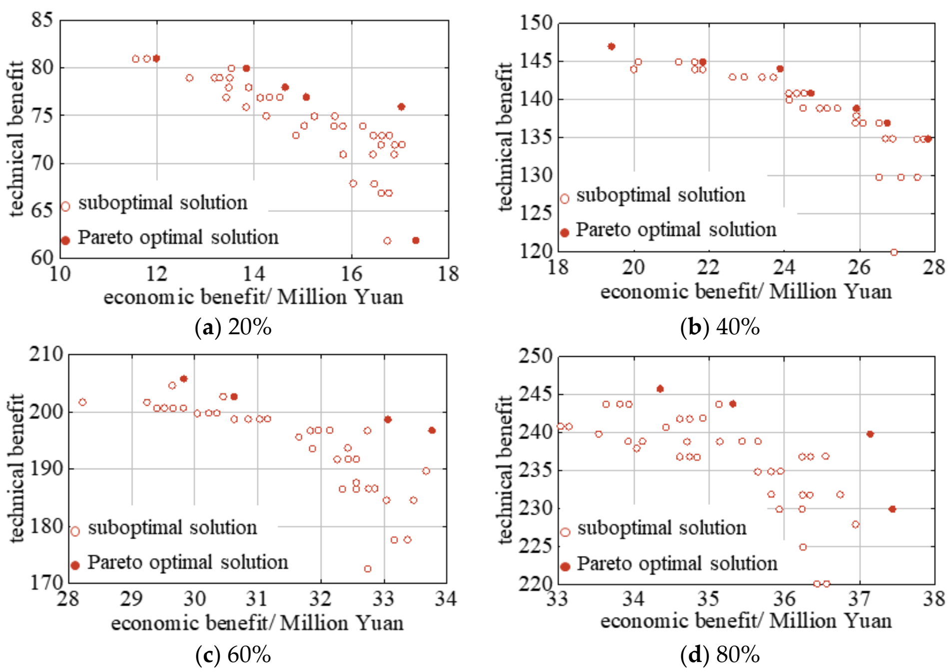


Figure 14. Sets of Pareto solutions with different budget–demand ratios.

Table 6. Multiobjective maintenance decision options for bridges with different budget–demand ratios.

Budget–Demand Ratio	Option	Bridge Number																				Economic Benefit (CNY 10^6)	Technical Benefit (Score)	Maintenance Cost (CNY 10^3)
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20			
20%	1	0	1	0	0	0	0	0	1	1	0	0	1	0	0	0	1	0	0	0	1	11.98	81	860
	2	0	1	0	0	1	0	0	1	0	0	0	1	0	1	0	1	0	0	1	0	13.82	80	860
	3	0	1	0	0	1	0	1	1	0	0	0	1	0	1	0	1	0	0	0	0	14.62	78	860
	4	0	0	0	0	1	0	1	1	1	0	0	1	0	0	0	0	0	0	1	1	15.06	77	860
	5	0	0	0	0	1	0	1	1	0	0	0	1	0	1	0	1	0	0	1	1	17.02	76	860
	6	0	0	0	1	1	0	1	1	0	0	0	0	0	1	1	0	0	0	1	1	17.32	62	860
40%	1	0	1	0	0	1	0	0	1	1	1	1	1	0	1	0	1	0	0	0	0	19.4	147	1720
	2	0	0	0	0	1	0	0	1	1	1	1	1	0	1	0	1	0	0	1	1	21.8	145	1720
	3	0	0	0	0	1	0	0	1	1	1	0	1	1	1	1	1	0	0	0	0	23.88	144	1730
	4	0	0	0	0	1	0	1	1	1	1	0	1	1	1	0	1	0	0	1	0	24.68	141	1720
	5	0	0	0	1	1	0	1	1	1	1	0	1	0	1	1	1	0	0	1	1	25.9	139	1710
	6	0	0	0	1	1	0	0	1	1	0	0	1	1	1	1	1	0	0	1	1	26.7	137	1680
	7	0	0	0	1	1	0	1	1	1	0	0	1	1	1	1	1	0	0	1	0	27.8	135	1690
60%	1	0	1	0	0	1	1	0	1	1	1	1	1	1	1	1	1	0	0	0	1	29.8	206	2600
	2	0	1	0	0	1	1	1	1	1	1	1	1	1	1	0	1	0	0	1	1	30.6	203	2590
	3	0	1	0	1	1	0	1	1	1	1	1	1	1	1	1	1	0	0	1	1	33.02	199	2550
	4	0	1	0	1	1	1	1	1	1	0	1	1	1	1	1	1	0	0	1	1	33.72	197	2560
80%	1	1	1	0	1	1	1	0	1	1	1	1	1	1	1	1	1	1	0	1	1	34.32	246	3460
	2	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	35.3	244	3450
	3	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	37.12	240	3440
	4	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	1	37.42	230	3330

Notation: “1” means that the bridge is maintained; “0” means that it is not maintained.

The sets of Pareto solutions at budget–demand ratios of 40%, 60%, and 80% (i.e., CNY 1.73 million, CNY 2.6 million, and CNY 3.46 million in maintenance funds, respectively) are shown in Figure 14b–d. Bridge maintenance programs for different budget–demand ratios are shown in Table 6.

This means that, given funding constraints, if the decisionmakers focus on improving the overall technical condition of the bridge network, then the option in Table 6 with the highest technical benefit should be chosen. If the focus is on the overall economic benefit of the bridge network, then the option in Table 6 with the highest economic benefit should be chosen. If both economic and technical benefits are important, then a compromise maintenance option can be chosen.

At the budget–demand ratio of 20%, the bridges to be maintained according to the principle of prioritizing the worst technical conditions are 13, 12, and 11. The bridges to be maintained according to the principle of maximizing the economic benefit are 4, 5, 7, 8, 14, 15, 19, and 20. While the bridges numbered 4 and 15 have key components of disease transmission deficiencies and priority for maintenance, the maintenance decision method proposed in this paper realizes that the maintenance funds are tilted towards the bridges with defective key components.

The results of the decisions for different budget–demand ratios based on the principles of prioritizing the worst technical conditions and maximizing the economic benefit are shown in Tables 7 and 8, respectively.

Table 7. Results determined according to principle of prioritizing worst technical conditions.

Budget–Demand Ratio	Bridges to Be Maintained	Economic Benefit (CNY 10^6)	Technical Benefit (Score)
20%	13, 12, 11	8.92	68
40%	13, 12, 11, 10, 9	13.48	115
60%	13, 12, 11, 10, 9, 6, 3, 2	17.48	160
80%	13, 12, 11, 10, 9, 6, 3, 2, 18, 1, 17, 8	22.98	214

Table 8. Results determined according to principle of maximizing economic benefit.

Budget–Demand Ratio	Bridges to Be Maintained	Economic Benefit (CNY 10^6)	Technical Benefit (Score)
20%	4, 5, 7, 8, 14, 15, 19, 20	17.32	62
40%	4, 5, 7, 8, 9, 12, 13, 14, 15, 16, 19	27.8	135
60%	2, 4, 5, 6, 7, 8, 9, 11, 12, 13, 14, 15, 16, 19, 20	33.72	192
80%	1, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 19, 20	37.42	230

A comparison of the benefits of the maintenance program based on the principle of maximizing the economic benefit and that based on the principle of prioritizing the worst technical condition is shown in Table 9. At a 20% budget–demand ratio, the pursuit of maximizing the economic benefits of maintenance with too little funding inevitably leads to an 8.8% reduction in the incremental technical benefit ratio. At 40%, 60%, and 80% budget–demand ratios, the incremental economic benefit ratios are 106.2%, 92.9%, and 62.8%, respectively, and the incremental technical benefit ratios are 17.4%, 20.0%, and 7.5%, respectively. It can be seen that the maintenance benefits of the principle of maximizing economic benefit are greater than those of the principle of prioritizing the worst technical condition. The decision-making method and fund allocation model proposed in this paper for bridge network maintenance applies to different budget–demand ratios for maintenance funds, and it can help decisionmakers to make scientific decisions on maintenance and thereby maximize its economic benefits.

Table 9. Comparison of results determined by two principles.

Budget–Demand Ratio	Incremental Economic Benefit Ratio	Incremental Technical Benefit Ratio
20%	94.2%	−8.8%
40%	106.2%	17.4%
60%	92.9%	20.0%
80%	62.8%	7.5%

Notation 1: Incremental economic benefit ratio = economic benefit of principle of maximizing economic benefit–economic benefit of principle of prioritizing worst technical condition/economic benefit of principle of prioritizing worst technical condition. Notation 2: Incremental technical benefit ratio = technical benefit of principle of maximizing economic benefit–technical benefit of principle of prioritizing worst technical condition/technical benefit of principle of prioritizing worst technical condition.

6. Conclusions

(1) Each part of the bridge is subjected to different traffic loads and environmental effects. The deck system is directly subjected to vehicle loads and rain and snow; thus, its deterioration rate is greater than those of the superstructure and substructure. The Guanzhong region is relatively economically developed, with busy traffic and more heavy vehicles; thus, the deterioration rates of its bridges are greater than those of the bridges in the Northern and Southern Shaanxi regions. Therefore, it is crucial to consider the environmental effects and traffic conditions when building bridge deterioration models;

(2) In view of the interconnection and mutual transmission of diseases among the bridge components, the pavement, expansion joints, and bearings are taken as the key components for disease transmission, and three typical disease transmission paths are accordingly proposed. In bridge maintenance, the diseases on the transmission paths should be taken as the focus of the maintenance to reduce the mutual influence of the diseases among the components;

(3) Considering the technical and economic benefits (related to the importance of the bridge and the diseases of the key elements) of maintenance, a model was developed using the NSGA-II for the allocation of bridge network maintenance funds under different budget–demand ratios. Comparing the results calculated using the traditional principle of prioritizing the maintenance of bridges in the worst technical conditions with those calculated using the principle of maximizing the economic benefits of maintenance, it was found that the economic benefit of the latter was 94.2%, 106.2%, 92.9%, and 62.8% higher than that of the former, and the technical benefit was—8.8%, 17.4%, 20.0%, and 7.5% higher than that of the former for different budget–demand ratios (20%, 40%, 60%, and 80%, respectively). Subsequent studies will validate this fund allocation model using more actual data to improve the utility of the model;

(4) This study proposes a bridge network maintenance decision method and maintenance fund allocation model to improve the efficiency of the limited bridge maintenance funds. Subsequent bridge maintenance management can utilize this model to make the best use of the funds. Moreover, this fund allocation model can be referred to in the development of bridge network maintenance specifications.

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