

## Article

# Pavement Maintenance Decision Making Based on Optimization Models

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**Abstract:** Pavement maintenance prioritization considering both quality and cost is an important decision-making problem. In this paper, the actual pavement condition index of city roads was calculated using municipal patrol data. A linear optimization model that maximized maintenance quality with limited maintenance costs and a multi-objective optimization model that maximized maintenance quality while minimizing maintenance costs were developed based on the pavement condition index. These models were subsequently employed in making decisions for actual pavement maintenance using sequential quadratic programming and a genetic algorithm. The results showed that the proposed decision-making models could effectively address actual pavement maintenance issues. Additionally, the results of the single-objective linear optimization model verified that the multiobjective optimization model was accurate. Thus, they could provide optimal pavement maintenance schemes for roads according to actual pavement conditions. The reliability of the models was investigated by analyzing their assumptions and validating their optimization results. Furthermore, their applicability in pavement operation-related decision making and preventive maintenance for roads of different grades was confirmed.



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**Keywords:** pavement maintenance and rehabilitation; decision optimization; pavement condition index; linear optimization; genetic algorithm

## 1. Introduction

Continuous urbanization in China has significantly increased the cumulative mileage of roads, which are considered the arteries of economic and social activities at the national and local levels. As an essential component of road infrastructure, a pavement is a type of hard surface made from durable surface material, which is able to withstand traffic and harmful environments. Because of increasing traffic volumes with heavy loads and the impacts of adverse environments, regular pavement maintenance is necessary to repair damage and mitigate degradation. A sufficient budget should be allocated to maintain the pavement at an appropriate condition, but insufficient budget is the primary obstacle of pavement maintenance [1]. When conducting large-scale pavement maintenance, it is important to consider the maintenance costs while ensuring that maintenance quality meets the requisite standards. The selection of a proper pavement maintenance scheme is a multiobjective optimization task. Therefore, determining the optimal maintenance scheme is crucial for decision making in pavement maintenance [2,3]. Decision making in pavement maintenance is a complicated, nondeterministic polynomial time (NP)-hard problem [4].

Maintenance personnel generally make judgments based on their personal experience when facing pavement maintenance tasks. Typical considerations include determination

of which roads need maintenance, measures to be adopted for pavement maintenance, estimation of the maintenance cost, and the deadline for completing the maintenance. However, decision making based on human experience cannot control pavement maintenance costs or evaluate whether the maintenance quality meets the relevant standards. This can subsequently lead to deterioration of road structures or pose challenges in the assessment of maintenance outcomes. Therefore, assessment and prediction of road deterioration [5] as well as establishment of the relationship between maintenance schemes and corresponding influencing factors [6] are crucial in decision making regarding pavement maintenance and fund allocation.

Recently, various decision-making methods for pavement maintenance have been proposed. These methods generally aim at improving quality and reducing costs under diverse scenarios. The most common methods include the analytic hierarchy process (AHP), decision making based on a clustering algorithm, and decision making based on a genetic algorithm (GA). The AHP method was first used for decision making in pavement maintenance by Saaty [7]. Farhan and Fwa proposed a pavement maintenance prioritization method based on AHP and developed a three-level hierarchy model to determine the priority ranking of different pavement maintenance schemes [8]. Li et al. developed an AHP-based pavement maintenance priority model by assigning weights to the factors influencing pavement conditions [9]. However, the selection of the indices and the determination of the index weights in the AHP method remained subjective. Thus, the method of selecting an optimal solution from all available plans determines the effectiveness of the final decision.

In recent years, with the development of machine learning and corresponding algorithms, some researchers began studying pavement maintenance decisions based on machine learning. Han et al. proposed a decision-making framework for pavement maintenance that combined a clustering algorithm with the PageRank algorithm [10]. In this framework, the pavements are first grouped into clusters by the clustering algorithm. Then, the maintenance ranking of the clustered road samples is determined according to the road conditions. Hafez et al. proposed a decision-making algorithm for pavement maintenance based on pattern recognition [11]. This method helps determine the optimal maintenance and repair plans for low-volume paved roads. GAs and traditional mathematical programming are often used to solve road M&R planning problems based on multiobjective optimization (MOO), but they also have their limitations. Elhadidy et al. [12] proposed a two-objective optimization model balancing minimum action costs and maximum conditions for used road networks and developed a GA-based procedure for solving the MOO problem. Hadiwardoyo et al. [13] described the development of a genetic algorithm based on multiobjective programming for pavement and investigated the optimal maintenance strategy options applied as function of road surface distress conditions with a lack of information related to monitoring data and evaluation. Sindi and Agbelie [14] explored the expected accuracy rates of network treatment options through a multiobjective optimization methodology that utilized a GA and mixed-integer programming; their method was capable of effectively assigning pavement maintenance tasks under certain conditions. Hafez et al. [15] performed large-scale optimization to compare the existing maintenance policy with an alternative strategy. Specifically, they incorporated a GA into the optimization model to address the issues associated with specific optimization constraints and the limitations related to low-volume roads during the optimization process. Alqaili et al. offered a new multiobjective stochastic algorithm called the integer search algorithm (ISA) [1]. The ISA and GA were applied to improve the performance condition rating (PCR) of pavement in developing countries and achieved this by maximizing the condition of the pavement with minimum costs at specified constraints. Santos et al. [3] proposed a novel adaptive hybrid GA that incorporated local search techniques to improve the overall efficiency and effectiveness of the search. Hosseininasab et al. [16] proposed two multiobjective evolutionary approaches to solve problems of road construction within a reasonable time. These approaches were combinations of different techniques, such as

GA, NSGA-II, the Frank–Wolfe algorithm, and the ordered logit model. The NSGA-II and its improved algorithms are popular for solving MOO problems [17,18]. To address the high computation complexity associated with pavement maintenance at the network level, Hankach et al. [19] developed a model to reduce the search space and formulated the original problem as a generalized assignment problem, which was a well-known problem in mathematical optimization. Ahmed et al. [20] proposed a chaotic particle swarm optimization algorithm to find the optimal solution for pavement maintenance. This algorithm could effectively resolve the maintenance and rehabilitation issues associated with flexible pavements. Ameri and Jarrahi [21] used condition indicators in the form of normalized values and developed technical constraints in a linear integer programming model to improve network-level pavement maintenance and rehabilitation planning. Chen et al. [22] proposed a network-level pavement maintenance and rehabilitation optimization model considering the costs of user travel time and vehicle fuel consumption. The model optimized the asphalt pavement performance evaluation method, including 11 different combinations, which could be easily extended to the study of more complex road networks considering other factors. Mataei et al. [23] proposed a model based on the cloud decision tree (CDT) theory, which included a general decision-making model and various decision trees for every province of the country.

As evident from the foregoing discussion, considerable research has been conducted to improve GAs and to utilize them for decision making in pavement maintenance because of their effectiveness in resolving multiobjective optimization problems. In this study, the pavement maintenance problem was introduced and formulated as a multiobjective decision-making problem. Subsequently, two optimization models were developed based on actual road conditions and applied to a real-world case. Sequential quadratic programming and the NSGA-II algorithm were used to solve the two models. Finally, the characteristics and the optimization space of the proposed models were analyzed based on the results obtained. Future plans for extending the proposed model were discussed in depth.

## 2. Problem Formulation

Pavement maintenance usually involves decision making at the macro level for selecting roads to be maintained under objective constraints and decision makers' priorities. In China, pavement maintenance is usually subject to territorial management within each administrative region. For example, each district and county has its own department responsible for decision making during pavement maintenance at the macro level. Typical decision-making tasks involved in pavement maintenance include the formulation of an annual pavement maintenance scheme, budget application, and quality control. When making pavement maintenance decisions in real scenarios, the degree of deterioration of the road network in a certain region is first evaluated based on daily patrol data. Pavement deterioration can be quantified as the pavement condition index (PCI), which is a numerical rating of pavement condition based on the type and severity of distresses observed on the pavement surface. PCI is represented by a numerical value between 0–100, where 0 is the worst condition and 100 is the best.

Subsequently, under the premise of considering the total maintenance cost and time, the annual maintenance scheme is formulated to improve the condition of roads with low PCIs. Thus, the maintenance of regional road networks must take multiple objectives into account, such as minimum maintenance cost and optimum maintenance quality. Therefore, determining a suitable approach to formulating an efficient maintenance scheme is a decision-making challenge.

The multiobjective maintenance problem of a road network in a specific region can be described mathematically as follows. Given the number of roads ( $N$ ), the area of each road ( $A$ ) that requires maintenance, the  $PCI$  of each road, and the total budget available for pavement maintenance ( $C$ ) in a certain region,  $m$  roads ( $m \leq N$ ) are prioritized for maintenance among the total  $N$  roads, such that (1) the total maintenance cost is less than

or equal to  $C$ , (2) the total maintenance cost is minimized, and (3) the maintenance quality is maximized. Selecting the appropriate roads based on human experience results in  $2^N$  combination schemes, because the decision variable is a Boolean representing whether a road is included in the maintenance schedule. Therefore,  $N$  cannot be excessively large, for when  $N$  is large, it is infeasible to select the final roads manually. This problem is NP-hard. To resolve it, heuristic algorithms were researched and developed aiming at an approximate optimal solution that could be a particularly sensible choice. In this study, a decision-making optimization model for pavement maintenance was solved by using NSGA-II. Optimum maintenance schemes were obtained that could ensure the maximal maintenance quality with minimal maintenance cost.

Figure 1 shows the overall procedure of decision-making optimization for pavement maintenance. The foundation is to evaluate road condition by pavement condition index, and the key is to establish optimization models of road maintenance. The models can be applied to provide optimal schemes for multiobjective decision making in regional road network maintenance. Many optimization models have been widely used, as found from engineering management and research literature, but these models of optimizing pavement maintenance have not been fully examined. In this paper, we examined how these models could be extended for our research goals and demonstrated how they could be used in pavement maintenance for an application area.

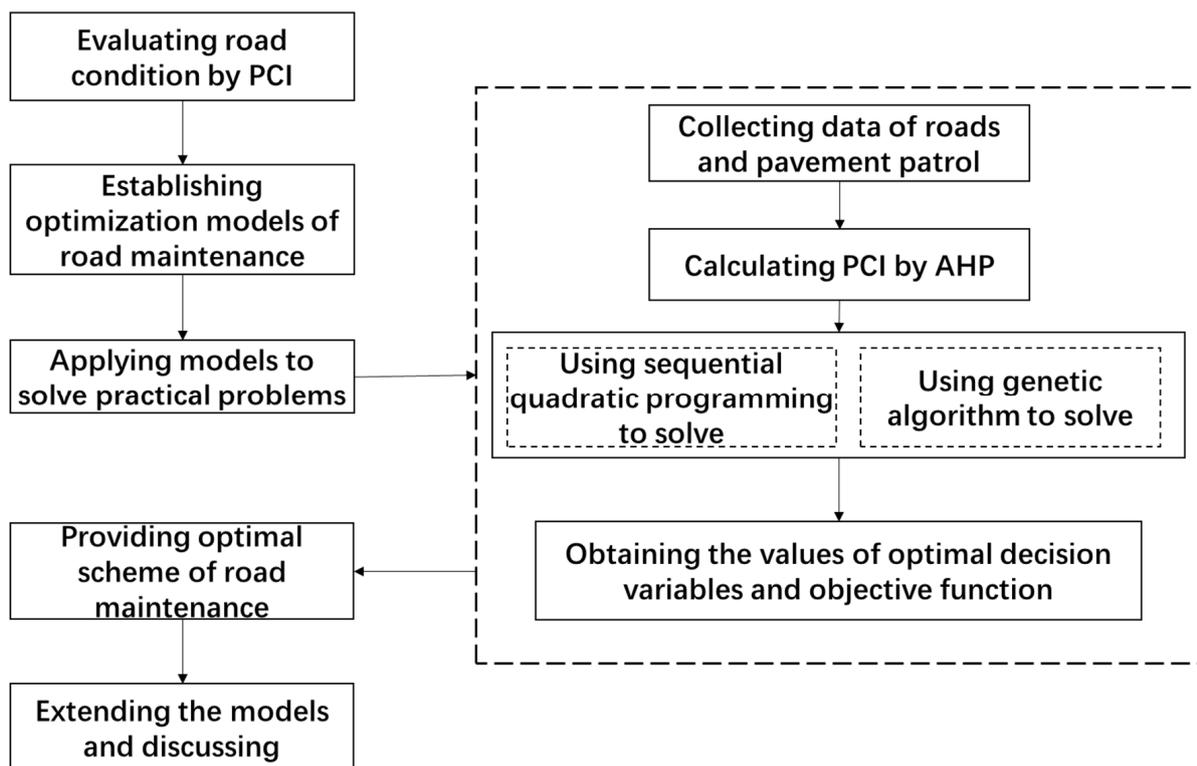


Figure 1. Overall flowchart of decision-making optimization for pavement maintenance.

### 3. Model Construction

The construction of the optimization models involved multiple steps, such as selecting the variables for decision making, setting up the model parameters, determining the objective function, and establishing the constraint conditions. In this section, two optimization models are established to resolve the road network maintenance problem.

### 3.1. Maximum Maintenance Quality–Limited Budget Model

To achieve optimal maintenance quality under a limited maintenance budget, a maximum maintenance quality–limited budget (MMQLB) model is built. The MMQLB model is a single-objective linear optimization model and is expressed as follows.

$$\max Z = \sum_{i=1}^n (PCI'_i - PCI_i) x_i \tag{1}$$

$$\text{s.t.} \begin{cases} \sum_{i=1}^n x_i Area_i \cdot P \leq Budget \\ x_i = 1 \quad \forall PCI_i < D \end{cases} \tag{2}$$

In these equations,  $x_i$  denotes the decision-making variable of the model, which represents whether the  $i$ th road requires maintenance. For each road, there exist two states in terms of whether maintenance is required. Setting  $x_i$  to 1 or 0 indicates that the road does or does not require maintenance at present, respectively.

Equation (1) represents the objective function of this model, where  $n$  is the total number of roads and  $PCI'_i - PCI_i$  represents the level of improvement in PCI (i.e., the maintenance quality) for a specific road.  $PCI'_i$  indicates the PCI of the road after maintenance and is set to 100 in this model; in other words, the road is assumed to be in perfect condition after maintenance. In contrast,  $PCI_i$  represents the original PCI of the  $i$ th road before maintenance. Equation (2) represents the constraint condition of the model, where  $Area_i$  represents the area ( $m^2$ ) of the  $i$ th road that requires maintenance.  $P$  is a constant that represents the maintenance cost per square meter of the road and is set as 200 CNY/ $m^2$ .  $Budget$  represents the total budget available for pavement maintenance, and  $D$  is a constant that represents the maintenance threshold of the road. When the PCI of a specific road drops below this threshold value, the road is judged to be of poor quality and require maintenance. Here, the default value of  $D$  is set to 70.

$PCI$  is selected as the parameter in the objective function because it is an important index for evaluating whether the road is in a satisfactory condition according to the Chinese “technical code of maintenance for urban road” [24]. In addition,  $PCI$  plays an important role in finalizing the maintenance scheme [25]. In this study, asphalt pavement is selected as the maintenance object. The equation for calculating the PCI of asphalt pavement is as follows:

$$PCI = 100 - \sum_{i=1}^n \sum_{j=1}^m DP_{ij} \omega_{ij} \tag{3}$$

In this equation,  $PCI$  ranges from 0 to 100;  $n$  is the total number of main deterioration types (here set as 4 for asphalt pavement exhibiting cracks, deformation, loosening, and other forms of deterioration);  $m$  is the total number of deterioration subtypes included in each main deterioration type; and  $DP_{ij}$  is the deduction caused by the  $j$ th subtype of deterioration in the  $i$ th main type.  $\omega_{ij}$  is the weight of the  $j$ th subtype of deterioration in the  $i$ th main type, which can be calculated by Equations (4) and (5) as follows:

$$\omega_{ij} = 3.0u_{ij}^3 - 5.5u_{ij}^2 + 3.5u_{ij} \tag{4}$$

$$u_{ij} = \frac{DP_{ij}}{\sum_{j=1}^m DP_{ij}} \tag{5}$$

When computing the  $DP_{ij}$  value, first, the actual deterioration density of a pavement, the ratio of the total area of the subtype  $j$  deterioration to that of the pavement, is calculated. The actual deterioration density is compared with the deterioration density of each deterioration subtype in Table 1, and  $DP_{ij}$  is found to be proportional to two numbers in two adjacent columns in Table 1. The  $u_{ij}$  is calculated by Equation (5) and  $w_{ij}$  by Equation (4) based on the  $DP_{ij}$  in Table 2. For example, the PCI of AnQing Rd. in the research area is calculated as shown in Table 2. The paved area of AnQing road is about 26,204.1  $m^2$ , with 1746.94 m of length and 4 lanes. The deterioration density is the ratio of the deteriorated area of each subtype and the paved area of AnQing road. The final  $PCI$  of AnQing road is 68.63, subtracting the sum of multiple of  $DP_{ij}$  and  $\omega_{ij}$  from 100.

**Table 1.** Deductions from pavement condition index (PCI) associated with different subtypes of deterioration on asphalt pavement.

Deterioration Type		Deterioration Density (%)					
		0.01	0.1	1	10	50	100
Crack	Slippage cracks	3	5	8	16	38	48
	Alligator cracks	5	8	10	20	45	70
	Spalling	8	10	15	30	55	80
Deformation	Subsidence	3	5	12	25	47	63
	Rut	2	7	12	25	45	55
	Upheaval	3	10	15	30	52	65
Loosening	Pit	10	15	25	40	65	72
	Edge failure	2	4	8	15	30	40
	Stripping	2	5	8	15	35	45
Others	Poor frame	3	8	12	12	12	12
	Damage of repaired section	2	5	8	15	25	33

**Table 2.** An example of calculating PCI using AnQing Rd.

Deterioration Type		Deterioration Area (m <sup>2</sup> )	Deterioration Density (%)	$DP_{ij}$	$u_{ij}$	$\omega_{ij}$	$\sum_{i=1}^n \sum_{j=1}^m DP_{ij} \omega_{ij}$
Crack	Slippage cracks	56	0.21	5.38	0.080	0.247	1.33
	Alligator cracks	0	0	0.00	0.000	0.000	0.00
	Spalling	300	1.14	15.24	0.228	0.547	8.34
Deformation	Subsidence	100	0.38	11.11	0.166	0.443	4.92
	Rut	0	0	0.00	0.000	0.000	0.00
	Upheaval	0	0	0.00	0.000	0.000	0.00
Loosening	Pit	60	0.23	16.43	0.245	0.572	9.40
	Edge failure	0	0	0.00	0.000	0.000	0.00
	Stripping	980	3.74	10.13	0.151	0.414	4.19
Others	Poor frame	0	0	0.00	0.000	0.000	0.00
	Damage of repaired section	488	1.86	8.67	0.129	0.367	3.19
Sum		1984		66.96			31.37

As mentioned previously, in this model, the road is assumed to be in perfect condition after maintenance. Therefore, the maintenance quality can be represented by  $100 - PCI_i$ . In other words, the larger the value of  $100 - PCI_i$ , the higher the maintenance quality.

### 3.2. Minimum Budget–Maximum Maintenance Quality Model

Optimal maintenance of multiple roads should seek to minimize the maintenance cost while maximizing the maintenance quality. To this end, a multiobjective optimization model named the minimum budget–maximum maintenance quality (MBMMQ) model is constructed and expressed by the following equations:

$$\max Z_1 = \sum_{i=1}^n (PCI'_i - PCI_i) x_i \tag{6}$$

$$\min Z_2 = \sum_{i=1}^n x_i Area_i \cdot P \tag{7}$$

$$s.t. x_i = 1 \forall PCI_i < D \tag{8}$$

In Equations (6) and (7), the function  $Z_1$  represents the maintenance quality, which equals the summation of improved PCI for all involved roads, whereas  $Z_2$  represents the total maintenance cost. In this model,  $PCI'_i$  is set as 100 to indicate that roads are assumed to be in perfect condition after maintenance.  $PCI_i$  denotes the original PCI of the  $i$ th road, and  $x_i$  is the state variable, which indicates whether the  $i$ th road requires maintenance. The value of  $x_i$  can be set only as 1 or 0, which signifies that the road does or does not require maintenance, respectively. Finally,  $Area_i$  and  $P$  have the same definitions as those in Equation (2). In Equation (8),  $D$  is the maintenance threshold; when the PCI of a specific road drops below threshold value, it is compulsory to maintain that road. Here,  $D$  is set to 70.

#### 4. Model Application

This section elaborates on the application of the proposed models in decision making for a real-world pavement maintenance problem. Using actual data, the global optimal results were obtained from the model.

##### 4.1. Dataset

In total, 149 roads under the jurisdiction of the Shushan District, a county-level district in Hefei, Anhui (China), were taken as the research objects. The deterioration data of these roads in 2019 were collected, and the maintenance area and pre-maintenance PCI were calculated by Equation (3). The roads were divided into three grades based on the National Standard of Road Classification: 9 expressways, 39 main roads, and 101 branch roads. For brevity, only a few roads in the three grades and their pre-maintenance PCI are listed in Table 3. Among the 149 roads, the average, minimum, and maximum PCI were 88.43, 67.89, and 100, respectively. There were 5 roads with PCI less than 70 and 26 roads with PCI equaling 100. As can be observed from the data, some roads were in poor condition, while others were in satisfactory condition. This reflects the level of diversity of the road dataset chosen for the study.

**Table 3.** PCI and other attributes of roads in Shushan District.

FID	Name	Grade	Maintenance Area (m <sup>2</sup> )	PCI <sub>i</sub>
1	AnQing Rd.	Main road	1984	68.63
2	BaiYanWan Rd.	Branch road	87	98.75
3	BanDao Rd.	Branch road	364	80.36
4	YanHe N. Rd.	Branch road	298	86.08
5	North 1st Ring Exp.	Expressway	1002	75.63
...	...	...	...	...
70	YanHe S. Rd.	Branch road	236	88.98
71	South 1st Ring Exp.	Expressway	320	78.69
72	NingXi Rd.	Branch road	0	100.00
73	NongXin Rd.	Branch road	125	92.52
74	PiHe Rd.	Main road	695	71.31
75	QianShan Rd.	Expressway	789	78.95
...	...	...	...	...
145	Changjiang Middle Rd.	Main road	302	86.36
146	ZhenXin Rd.	Branch road	0	100.00
147	ZhiWuYuan E. Rd.	Branch road	123	90.20
148	ZhiWuYuan S. Rd.	Branch road	231	89.54
149	HaiTang Rd.	Main road	33	99.15

##### 4.2. Solving the Models

Prior to solving the models, the pre-maintenance PCI, maintenance area, maintenance cost per unit area, and maintenance threshold for each road were first fed into the model as input parameters. Subsequently, the optimization models were implemented, and the values of the decision-making variables and the objective functions were calculated by

using sequential quadratic programming and the NSGA-II algorithm. Finally, the optimal pavement maintenance scheme was determined based on the results obtained from the model. The first model was solved using the sequential quadratic programming method.

Because the multiobjective model could be solved by a GA, the second model was solved by using the NSGA-II algorithm in our research. The calculation steps involved in the NSGA-II algorithm are as follows. First, multiple sets of optimization solutions for pavement maintenance are randomly generated and are referred to as the solution population. Subsequently, these solution sets are ranked based on the maximum pavement maintenance quality and the minimum pavement maintenance cost calculated for each set of solutions. This process is also known as rapid nondominated sorting of the solution population. Next, a new generation of solutions is obtained through selection, crossover, and mutation of the solution population. The new solutions are the offspring of the first-generation solutions. Starting from the second generation, the parent and offspring populations are combined to perform rapid nondominated sorting. Simultaneously, the crowding degrees are calculated for each individual in the nondominated layer. Suitable individuals are then selected according to their crowdedness and the nondominated relationship to form a new parent population. Finally, a new offspring population is generated through selection, crossover, and mutation of the new parent population.

The final solution set of the objective function can be obtained by repeating the aforementioned process continuously until the maximum number of iterations is reached. NSGA-II can select multiple nondominated individuals that form an optimal set of trade-off solutions called the Pareto set. The pavement maintenance scheme can then be formulated according to the solution results. Some researchers have proposed simpler coding methods to represent complex evolutionary phenomena. These methods can realize heuristic searches in the complex search space and can determine the global optimal solution of the objective function with high probability through a simplified genetic process.

#### 4.3. Results of the Models

Table 4 shows the optimal solutions obtained by the MMQLB model with different budgets. The best pavement maintenance quality provided by the model was 1724.29, which equaled the sum of the improved PCI for all roads; meanwhile, the maintenance cost was 10.199 million CNY. Because of actual budget limitations, some roads had to be eliminated from the full maintenance scheme. The maintenance quality was 154.51 with the cost = 1,567,200 CNY if only the worst roads under 70 PCI were to be maintained. The optimal maintenance quality was 324.861 with a cost = 1,999,600 CNY, and the maximum maintenance was 1025.2 under a 5 million CNY budget. The maximum improvement to PCI was 1479.52 under an 8 million CNY budget. The optimal maintenance was 1702.64, and the cost was 9,991,800 CNY under a budget of 10 million CNY. Table 5 shows the PCI improvements to 149 roads in the optimal scheme obtained by MMQLB model under the 5 million CNY budget limitation. According to the optimal scheme, the PCI improvements of each road equaled the difference between 100 and the original PCI if a road was selected to be maintained; otherwise, its PCI improvement was zero.

**Table 4.** Optimal solutions obtained by MMQLB model with different budgets.

Optimal Solutions	Maintenance Quality (Sum of Improved PCI)	Maintenance Cost (CNY)
Necessary maintenance (PCI < 70)	154.51	1,567,200
Optimal maintenance with 2 million CNY budget	324.861	1,999,600
Optimal maintenance with 5 million CNY budget	1025.2	4,967,400
Optimal maintenance with 8 million CNY budget	1479.52	7,998,600
Optimal maintenance with 10 million CNY budget	1702.64	9,991,800
Full maintenance without budget constraint	1724.29	10,199,000

**Table 5.** PCI improvements of 149 roads according to the optimal scheme obtained by the MMQLB model with a 5 million CNY budget limitation.

Road Number (from Left to Right)	PCI Improvements of Each Road (Difference between the Output PCI from the Model and Original PCI of Each Road)									
No. 1–10	31.37	0.00	19.64	13.92	0.00	0.00	17.86	27.14	0.00	0.00
No. 11–20	2.31	18.65	0.00	0.00	30.45	0.00	0.00	2.13	0.00	18.68
No. 21–30	23.11	16.79	0.00	2.86	13.32	0.00	0.00	2.11	0.00	0.00
No. 31–40	30.47	0.00	26.32	0.00	0.00	2.63	18.19	0.00	0.00	0.00
No. 41–50	0.00	1.76	0.00	32.11	17.74	0.00	19.94	26.46	13.35	25.43
No. 51–60	0.00	0.00	0.00	0.00	10.35	7.78	0.00	0.00	0.00	25.46
No. 61–70	0.00	28.88	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
No. 71–80	11.02	21.31	0.00	7.48	28.69	0.00	0.00	0.00	0.00	24.70
No. 81–90	25.46	0.00	0.00	30.11	0.00	0.00	19.91	21.84	19.40	0.00
No. 91–100	0.00	9.78	0.00	0.00	0.00	0.00	7.37	0.00	12.11	13.10
No. 101–110	21.37	0.00	0.00	0.00	10.13	0.00	9.61	10.32	7.68	14.32
No. 111–120	11.22	6.99	9.24	0.00	15.46	0.00	0.00	8.41	0.00	0.00
No. 121–130	0.00	23.90	0.00	10.61	0.00	0.00	0.00	0.00	0.00	0.00
No. 131–140	3.31	11.76	9.42	0.00	0.00	0.00	0.00	0.00	0.00	0.00
No. 141–149	0.73	0.00	15.76	0.00	11.39	13.64	0.00	9.80	10.46	—

The optimal maintenance scheme of 1702.64 PCI improvement under a 10 million CNY budget is shown in Figure 2 using a thematic map of 149 roads in the Shushan District. All roads with a PCI smaller than 70 required maintenance according to the constraint set in the MMQLB model. Each road was labelled by its FID and name in the map. For the roads in red, the corresponding decision-making variables were calculated to be 1 under the optimization model, implying that these roads had to be maintained. For the roads in blue, the decision-making variable was calculated to be 0 under the optimization model, signifying that these roads did not require maintenance.

Next, Figure 3 shows the resulting Pareto front obtained by the MBMMQ model. The objective function was solved by the NSGA-II algorithm and converged to stable values at approximately the 3000th generation. The first objective function was maximizing maintenance quality in the  $x$ -axis direction, and the second was minimizing maintenance cost in the  $y$ -axis direction. The solution set included many optimal solutions, represented by star points, which made up the Pareto front. Three solutions are highlighted along with their objective function values in Figure 3.

The two optimal models were applied to the integrated management system for municipal facilities in Shushan Dist., Hefei, Anhui (China). Since 2018, the Municipal Engineering Management Office in Shushan Dist. used the system for pavement decision making. The total improved PCI of road maintenance increased by 15% in 2019, while the budget for maintenance remained almost the same.



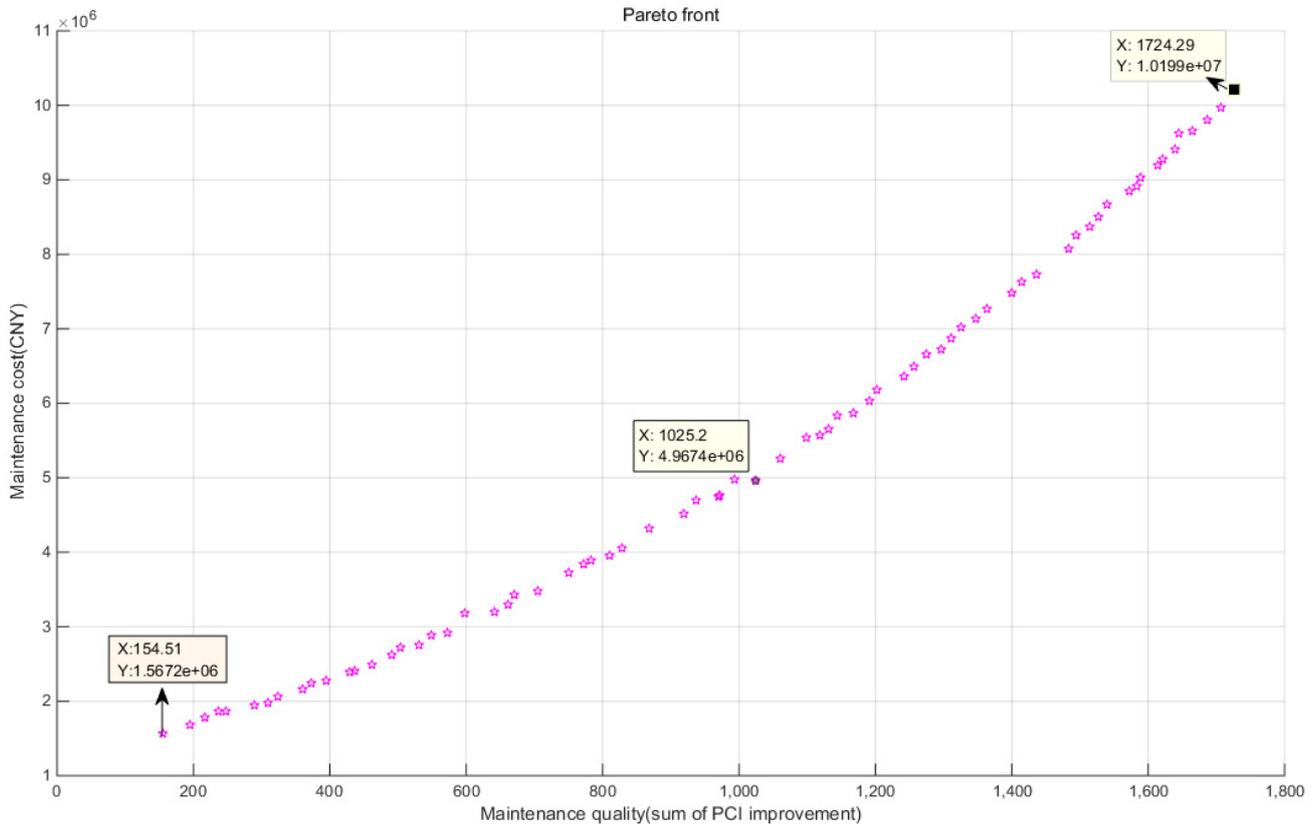


Figure 3. Pareto front of the MBMMQ model solved by genetic algorithms.

## 5. Discussion

In this section, we discuss the suitability of the developed models, the validation of the obtained results, and extensions of the multiobjective model.

### 5.1. Analysis of Model Suitability

The theoretical suitability of the proposed models was analyzed as follows. A linear optimization model must satisfy the following implicit assumptions.

(1) Assumption of linearization: a function is considered linear [26] when the following equation is satisfied:

$$f(x_i) = \sum_{i=1}^n c_i x_i + K \quad (9)$$

In the equation,  $K$  and  $c_i$  are constants. The objective functions of the two proposed models can be converted to the form shown in Equation (9). Therefore, these objective functions can be considered as linear functions.

(2) Assumptions of proportionality: A change in the decision-making variable should cause the objective function to change proportionally. Because the relationship between the decision-making variable and objective function can be expressed in the form given in Equation (13) for both models, the assumption of proportionality is satisfied for the decision-making variable and the objective function.

(3) Assumption of additivity: The value of the objective function should equal the sum of the individual contributions from each decision-making variable to the objective function. This assumption is satisfied for all models, as is evident from their equations.

(4) Assumption of the fixed parameter: All the parameters are fixed constants, and no random factor is introduced into the analysis. The PCI used in all models is also a fixed parameter. Therefore, this assumption is also satisfied.

### 5.2. Validation of Results Obtained from the Models

The proposed MMQLB model is a single-objective linear optimization model that can provide an exact result. Its result is a maintenance scheme that maximizes the maintenance quality under a limited maintenance budget, such as some key schemes shown in Table 4. Meanwhile, the MBMMQ model, which is a biobjective optimization model, was solved by NSGA-II, a heuristic algorithm. In Figure 3, each point represents an optimal maintenance scheme solved by the biobjective optimization model for 149 roads. Among the optimal maintenance schemes suggested by the MBMMQ model, three schemes were highlighted along with their objective function values, and the costs exactly matched the results obtained by the MMQLB model, satisfying the corresponding cost constraints. The best PCI improvement was 1724.29, with a cost of 10,199,000 CNY; the maximum PCI improvement was 1025.2, with a cost of 4,967,400 CNY; and the necessary PCI improvement was 154.51, with a cost of 1,567,200 CNY. Some solutions of MMQLB were included in the solution set of MBMMQ. This suggests that the results of the MMQLB model verified the part results of the MBMMQ model in this case. For this reason, we believe that the solutions found by the NSGA-II were indeed optimal and that they formed the Pareto front for our biobjective maintenance decision-making problem. The overall shape of the Pareto front indicated the same trend of increasing sum of minimal maintenance cost with the total improved quality. The Pareto front for our problem was discrete, but more importantly, it had a nonconvex shape. This was clearly shown when sum of PCI improvement reached around 1000, where the front took an obvious turn. This suggests that it is often difficult to use a heuristic algorithm to obtain an exact convex Pareto front for a multiobjective decision-making problem.

### 5.3. Extension of the Multiobjective Model

This section focuses on extension of the multiobjective model. Considering different road grades, expressways have a higher maintenance priority than main roads. Moreover, main roads usually have a higher maintenance priority than branch roads. The MBMMQ model was extended accordingly, as follows:

$$\max Z_1 = \sum_{i=1}^n (PCI'_i - PCI_i)w_i x_i \tag{10}$$

$$\min Z_2 = \sum_{i=1}^n w_i x_i Area_i \cdot P \tag{11}$$

Here,  $w_i$  denotes the grade of road  $i$ , which is set to 1.5, 1, or 0.5 when road  $i$  is an expressway, a main road, or a branch road, respectively. Based on this revised model, the effects of the different road grades and maintenance schemes were further determined, as shown in Figure 4. Compared with the original solution, the maintenance costs and quality are slightly different, which was primarily due to different road PCI values and maintenance areas between expressways and branch roads. These results indicated that the revised model is suitable for multiple road grades.

Because of constraints on pavement maintenance, a road may be only partially maintained, and its PCI may be lower 100 after maintenance.  $PCI'_i$  could replace  $x_i$  as a decision-making variable, which represents the PCI of the road after maintenance. Based on the MBMMQ model, the third MOO model is proposed as follows.

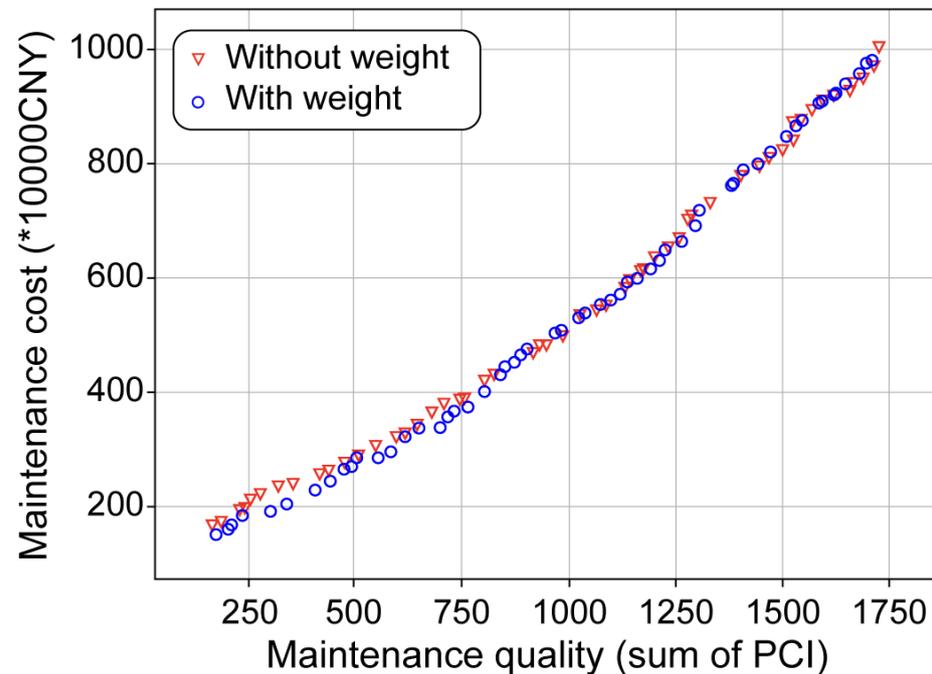
$$\max Z_1 = \sum_{i=1}^n (PCI'_i - PCI_i) \tag{12}$$

$$\min Z_2 = \sum_{i=1}^n \frac{Area_i \cdot P \cdot PCI'_i}{PCI_i} \tag{13}$$

$$s.t. PCI_i \leq PCI'_i \leq 100 \tag{14}$$

In this model,  $PCI'_i$  is selected as the variable, which can vary from  $PCI_i$  to 100. The constants  $PCI_i$ ,  $Area_i$ , and  $P$  are the same as those in Equation (2). Therefore, when calculating the maintenance cost for a specific road,  $PCI'_i / PCI_i$  should be incorporated

into Equation (13) to consider the effect of PCI improvement on the maintenance area. This model is suitable to maintain quantitatively each selected road and can be solved by NSGA-II.



**Figure 4.** Comparison between the pavement condition index (PCI) values of the roads before and after maintenance calculated by the MBMMQ model.

## 6. Conclusions

In multiobjective decision making of pavement M&R, some main research fields have emerged, such as sustainable pavement maintenance management, optimization of decision models with high-dimensional objectives, nonlinear planning, and high-dimensional variables, which have received increasing attention [27]. Here, actual decision-making problems of pavement maintenance were investigated, and an overall procedure for decision-making optimization was proposed. First, PCI was calculated based on the deterioration type and area to evaluate road conditions using the AHP method. Then, two models, named MMQLB and MBMMQ, were developed. The first model was a single-objective linear optimization model, whereas the other was a MOO model. These models were employed for a real-world case involving the maintenance of 149 roads in Shushan District, Hefei, China. First, the pavement condition data of these roads were recorded and imported into the models. The models were then solved using sequential quadratic programming and a GA. Finally, appropriate pavement maintenance schemes were established based on the solutions of the optimization models. Among the optimal maintenance schemes of the MBMMQ model, some optimal values in the pair of maintenance quality and cost exactly matched the results obtained by the MMQLB model with the corresponding cost constraints. This indicated that the MMQLB model could achieve similar decision making to the MBMMQ model by setting different maintenance constraints. According to one nonlinear constraint of MMQLB, it could be improved to substitute the nonlinear formulation and reduce the difficulty of solving the problem in future research. In practical scenarios, the pavement maintenance cost is also dependent on the time taken and priority levels of the road grades. Therefore, the parameters used in the proposed models will be further extended in future studies to reflect real-world scenarios better and to broaden the applicability of the models.

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