Energy & Buildings 290 (2023) 113096

Contents lists available at ScienceDirect

Energy & Buildings

journal homepage: www.elsevier.com/locate/enb

Numerical analysis of a multi-objective maintenance decision-making model for sustainable highway networks: Integrating the GDE3 method, LCA and LCCA

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ARTICLE INFO

Keywords:
Asphalt pavement maintenance
Multi-objective maintenance decision-making
Generalized differential evolution algorithm
Life cycle assessment and cost analysis
Pavement sustainability

ABSTRACT

A pavement maintenance and rehabilitation decision-making model plays a significant role in the sustainable development of highway networks. However, various maintenance and rehabilitation models lack the capacity to provide multi-objective maintenance decision-making strategies, which are solely concerned with reducing maintenance costs. This study aims to propose a multi-objective maintenance decision-making model, called the Pavement Maintenance-Generalized Differential Evolution 3 (called PM-GDE3), by integrating the pavement condition indices and the generalized differential evolution 3 (GDE3) method. Economic aspect, pavement sustainability, and environmental dimensions were considered in the proposed model to increase the flexibility of pavement management. In this study, the widely-used PAVER maintenance system,which represents a conventional M&R decision-making model and the PM-GDE3 model were applied to estimate the optimal maintenance and rehabilitation schedules for the highway networks, and the results from these models were compared. The results show that the maintenance strategy obtained from the PM-GDE3 model maintains the highway in an acceptable condition. In addition, it has been found that the PM-GDE3 model saves 30.9% of maintenance expenses, about 169 million CNY, 16.9% of carbon emissions, around 4,469 kt, and 11.6% of energy consumption, 2.8GJ, for as long as 30 service years compared to the PAVER model. The PM-GDE3 model outperforms the widely used PAVER maintenance system due to its capacity to propose the optimal solution by establishing a real-time simulation with numerous pavement conditions after maintenance application. This field is the first attempt to combine pavement performance prediction model, life cycle assessment method and life cycle cost assessment. The achievements of the paper are expected to combat the impending energy crisis and climate change impacts of pavement maintenance and rehabilitation.

1. Introduction

As a result of the combined impact of increasing vehicular loads and natural environmental factors, the durability of asphalt pavements decreases over time, leading to various degrees of damage in pavements [1]. Repairing these damaged asphalt surfaces and maintaining the durability of asphalt pavement requires significant time and financial investment from highway maintenance departments. When maintenance is not performed in a timely manner, pavement deterioration becomes progressively worse, causing increased maintenance costs, carbon emissions, and energy consumption [2,3]. In addition, deteriorating asphalt pavement conditions negatively impact vehicle riding condition, leading to higher fuel consumption and emissions. This not only results in increased expenses for vehicle owners but also has detrimental effects on the environment [4]. In recent years, the focus of highway maintenance departments has shifted towards asphalt pavement decarbonization, with the aim of extending the service life of highway asphalt pavements while minimizing both maintenance costs and environmental damage [5]. The success of low-carbon asphalt pavement initiatives depends on the development of well-thought-out

Abbreviations: APA, Asphalt Pavement Alliance; DE, Differential Evolution; GDE3, Generalized Differential Evolution 3; GA, Gene Algorithm; LCA, Life Cycle Assessment; LCCA, Life Cycle Cost Analysis; LCA-LCCA, Life Cycle Assessment-Life Cycle Cost analysis; M&R, Maintenance and Rehabilitation; NSGA-II, Non-dominated Sorting Genetic Algorithm II; PCI, Pavement Condition Index; PMS, Pavement Maintenance System; PM-GDE3, Pavement Maintenance-Generalized Differential Evolution 3; RDI, Rutting Depth Index; RQI, Riding Quality Index; SWMM-FTC, Storm-Water Management Model-Flow Transmission Chain.

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https://doi.org/10.1016/j.enbuild.2023.113096
Received 6 September 2022; Received in revised form 10 April 2023; Accepted 18 April 2023
Available online 21 April 2023
0378-7788/

maintenance plans. These plans should involve identifying critical areas, creating maintenance strategies for different regions, prioritizing high-traffic roads, and carrying out regular inspections and maintenance. This approach maximizes asphalt pavement service life, reduces maintenance frequency, and lowers energy consumption and carbon emissions. Despite these efforts, current maintenance models often fall short in addressing highway project decarbonization effectively, as most models concentrate on a single maintenance goal, such as cost reduction or partial pavement performance improvement. Given the limited maintenance funds and resources available, there is a pressing need for an efficient asphalt pavement infrastructure management model that can minimize environmental impacts while supporting the sustainable development of asphalt pavements [6,7].

Asphalt pavement maintenance decision-making frameworks can be classified based on different objectives, decision variables, constraints, and algorithms. They primarily fall into three categories: experience and expert judgment, rule-based methods, and statistical methods [8]. Experience and expert judgment rely on past experience and expert opinions to develop maintenance plans, including visual inspections, regular maintenance, and timely repairs according to pavement conditions. The advantages of this approach are its simplicity, cost-effectiveness, and ease of implementation. However, it is subjective and lacks quantification. Rule-based methods involve formulating maintenance plans according to pre-established rules, such as pavement conditions, traffic volume, and service life, to determine different types of repair schemes. This approach is easy to understand and implement, but the rule-setting process can be subjective and inflexible. Statistical methods primarily analyze historical data and develop models to predict future pavement conditions and establish reasonable maintenance plans. For example, regression analysis and time series analysis can be used to forecast pavement conditions and required maintenance methods. The advantage of this approach is that it considers the influence of historical data, but the prediction of future conditions may be uncertain. Considering the limitations of the three methods mentioned above, this article proposes an optimization model-based method for formulating maintenance and repair strategies for large-scale highway asphalt pavements. This method mainly involves establishing a maintenance decision model, seeking the optimal solution based on different objectives and constraint conditions, and using optimization algorithms. This approach aims to minimize maintenance costs, energy consumption, and carbon emissions during the maintenance process and maximize the service life of asphalt pavements. The advantages of this method include considering various factors and achieving high solution efficiency [9].

Table 1 summarizes the latest representative studies in the field of asphalt pavement management, which attempt to optimize asphalt pavement highway maintenance strategies and provide segment-specific solutions. In the field of asphalt pavement management, optimizing project-level pavement maintenance strategies is an important issue. It involves formulating reasonable repair plans based on factors such as pavement conditions, traffic volume, and service life, ultimately extending pavement service life while reducing maintenance costs and environmental impacts [7,8]. The latest representative studies mainly involve optimization algorithms, including genetic algorithms (GA) and dynamic programming methods. Genetic algorithms are a global optimization algorithm based on the ideas of genetic evolution and are widely used in asphalt road management. The advantages of genetic algorithms lie in their ability to handle large numbers of parameters and variables, as well as their capacity to search for global optimal solutions. Recent research indicates that when using genetic algorithms for pavement maintenance decision-making, the accuracy of solutions can be improved by changing the fitness function and adjusting the algorithm's parameters. Furthermore, deep learning techniques can be used to predict pavement conditions, allowing for more accurate determination of maintenance strategies. However, there are still some drawbacks. Genetic algorithms have weaker local search capabilities and can easily become trapped in local optima when dealing with multi-peak functions and non-linear problems. Additionally, genetic algorithms require adjusting many parameters, making it difficult to determine the optimal ones [8,10]. Dynamic programming (DP) methods are also widely applied in asphalt road management. The advantages of dynamic programming include finding global optimal solutions without encountering dead loops or local optima. The latest research indicates that dynamic programming algorithms can transform pavement maintenance problems into optimal control problems and find optimal solutions using methods such as simulated annealing algorithms. Researchers have also explored combining dynamic programming algorithms with deep learning to enhance the accuracy of solutions [11,12]. However, dynamic programming has its disadvantages. When dealing with high-dimensional problems, the computational complexity increases exponentially, resulting in long solution times. Moreover, dynamic programming requires accurate pavement condition data and corresponding decision variables, necessitating high data precision and quality [13,14].

Recently, some researchers have utilized the third Evolution Step of Generalized Differential Evolution (GDE3) to solve maintenance optimization problems for urban drainage pipelines and other infrastructure [15–17]. The GDE3 algorithm is a global optimization algorithm and an extension of the differential evolution algorithm. It can be used to optimize multi-objective problems and performs well in solving nonlinear, non-convex, and high-dimensional optimization problems, aiming to maximize long-term cumulative returns [18–20]. It has advantages over other optimization algorithms such as Genetic Algorithm (GA) [8,21], Dynamic Programming (DP) [22,23], and Reinforcement Learning (RL)[24]. Compared to GA, the GDE3 algorithm is more sensitive to changes in the objective function and can dynamically adjust differential evolution strategies and mutation factors according to the features of the objective function, better adapting to different problem types [15]. In contrast, GA typically employs fixed crossover and mutation operations, is less sensitive to changes in the objective function, and may encounter issues such as premature convergence and stagnation [17,18]. Compared to DP and RL, the GDE3 algorithm is primarily used to solve continuous optimization problems, while RL and DP methods mainly tackle discrete optimization problems [25]. In terms of convergence speed and computational efficiency, the GDE3 algorithm is generally faster in convergence than GA, as it employs dynamic mutation strategies, striking a better balance between population diversity and convergence [26]. GDE3 is typically more efficient than RL and DP methods, as it uses differential evolution operators that allow for rapid convergence and finding global optimal solutions. In contrast, RL and DP methods require complex calculations and iterations. The training process for RL algorithms involves interactions in the environment, which may be limited by environmental states and require more time to find the optimal solution. As a result, the GDE3 algorithm is garnering increasing attention in the field of engineering management. Moreover, the GDE3 algorithm can address the limitations of the above methods in

Table 1
Summary of current researches for decision-making of highway maintenance.

ID	Method	Pavement Condition	Economic indicators	Environmental indicators	
			Cost	Carbon Emission	Energy Consumption
1	NSGA-II [21]	IRI, CCI	√		
2	NSGA-II [7]	PSI	√	√	√
3	DP[27]	PSR	√		
4	RO[28]	IRI	√	√	
5	DP[29]	DI	√		
6	DP[30]	PSI	√	√	
7	GA[8]	SDI	√		
8	GA[10]	CCI	√		

asphalt pavement maintenance decision-making. Once the objective function, constraint conditions, and evaluation function are determined, the GDE3 algorithm can be used to search for the optimal maintenance strategy. Specifically, the algorithm generates a series of decision sets and creates new decision sets through crossover and mutation operations on these sets. Then, the evaluation function assesses each newly generated decision set, and the optimal decision sets are selected based on evaluation results. In summary, using the GDE3 algorithm can help determine the optimal decisions for asphalt pavement maintenance, ultimately reducing maintenance costs, lowering carbon emissions, and improving pavement service life.

Although previous researchers have made contributions, there are still some limitations. First, the uncertainty of environmental and social impacts: decision models typically only consider the technical and economic impacts of asphalt pavement maintenance, without taking into account the effects on the environment and society, such as carbon emissions and social costs. How to incorporate these factors into the decision model is an issue that needs to be addressed. Additionally, the complexity and computational costs of existing asphalt maintenance decision models: as the number of pavements and maintenance strategies increases, the computational cost of decision models rises dramatically. Therefore, more efficient algorithms and methods need to be sought to address this issue. Existing asphalt maintenance decision models are only applicable to the formulation of maintenance strategies for specific road sections or individual lanes. In the context of large-scale highway network maintenance, the same maintenance strategy is applied to different road sections. However, simply applying the same maintenance strategy to different road sections can lead to resource waste or failure to adequately meet the maintenance needs of the sections. In asphalt pavement maintenance, it is necessary to adopt different maintenance strategies according to the actual situation and needs of each road section, in order to maximize road service life while avoiding resource waste. To solve this problem, this study will apply the GDE3 algorithm to learn and develop maintenance plans for different asphalt pavement damage situations and severity levels in selected highway sections in Guangdong Province. Based on the characteristics and needs of large-scale highway asphalt pavements, suitable maintenance strategies will be selected. The goal is to minimize total cost and maximize pavement service life, while considering the characteristics and needs of different road sections and adopting different maintenance strategies. This approach can avoid the issue of using the same maintenance strategy for different road sections, and also maximize the realization of low-carbon and sustainable development goals for asphalt pavements.

2. Research area and data source

In this study, the Guangshen highways in Guangdong Province, which have accumulated 12,000 km of highway mileage by the end of 2022 [31], were selected as the research object. There are over 5672 km of highways with a service life of more than 10 years, of which 3509 km of highways have been in service for about 15 years in Guangdong. As a result, over half of the highways have entered the critical period of pavement maintenance and rehabilitation. A 1 km fixed-length section division plan was adopted, which is simple to implement and calculate for statistical analysis [30,32]. The input local data for the establishment of the maintenance and rehabilitation decision-making model considered the cumulative equivalent single-axle loads, the pavement conditions, a large number of M&R actions for the deteriorated pavement (such as the type and cost of maintenance, carbon emissions, and energy consumption), and pavement structures, which were obtained from the Center of Maintenance Analysis Platform of Guangdong Highway Affairs.

3. Methodology

Fig. 1 shows a flowchart of the present research work with a brief description of the applied methodology. The PM-GDE3 model was developed to achieve sustainable development of highway networks in Guangdong. A series of local calibration pavement performance models, established in a previously published article [33], were applied to predict the highway pavement performance conditions. The cost of the M&R strategy, the carbon emissions, and the energy consumption were calculated using the LCA-LCCA method [1]. The widely used maintenance tool, PAVER [34], was selected for comparing its results with those of PM-GDE3 in terms of estimating the efficiency and validity of the determined M&R alternative used in highway maintenance.

3.1. GDE3 algorithm

In this study, the GDE3 algorithm was employed to address the pavement M&R scheme optimization problem, including the decision factors, the objective functions, and the conflicting goals [19]. For the implementation of our PM-GDE3 model, we employed the Generalized Differential Evolution 3 (GDE3) algorithm using the software, jMetal (version 5.10), which is a widely-used tool for solving multi-objective optimization problems.

Referring to the recently published literature, the optimization of pavement maintenance and rehabilitation is a time-consuming procedure because of the various maintenance actions of selection, arrangement, and determination, and a large number of pavement prediction models and the LCA-LCCA model calculation that is needed to be performed for each step [35]. There are a few algorithms that can determine the multi-objective M&R strategy. The GDE3 method has been considered one of the ideal methods to optimize the problem of sequential maintenance actions, thus providing a beneficial situation for economic promotion and environmental preservation [36]. The GDE3 algorithm has been shown to outperform the conventional optimization approaches, including NA and NSGA, in global optimization with a large number of objective functions [9]. Based on the prominent advantage of the GDE3 algorithm, it was selected for determining the M&R strategy. The outperformed mutation operator and the improved crossover of GDE3 play a significant role in finding the optimal M&R planning, which maximizes the long-term benefits of the environmental and economic aspects [15–19]. The establishment of GDE3 is as follows:

(1) Initialize the control parameters of the GDE3 algorithm (population size, cross probability factor, scaling coefficient, elite set size, maximum iterations, etc.) and the population. Calculate the fitness of each target.
(2) Add the population individuals to the external elite set using an elite set maintenance strategy.
(3) Calculate the mutation, crossover, and selection operation of the DE algorithm for each population individual as follows: the variant operation and the standard DE algorithm, but by adding the boundary constraints. If the boundary constraint is exceeded, the dimension data is randomly generated within the boundary range. The cross operation and the standard DE method are selected according to the cross probability factors. To avoid selecting one-dimensional data for random variation, during the selection operation, the objective function is first solved to obtain the fitness of each target, and the dominant relationship between the experimental individual and order and the standard individual is estimated. If the target individual governs the test, perform the next cycle. Otherwise, if the test individual governs the target individual, add the experimental individual to the elite set update operation. On the other hand, if the experimental individual and the target individual do not control, add the trial individual directly to the elite set update operation. Determine whether each individual in the population is manipulated once to update the

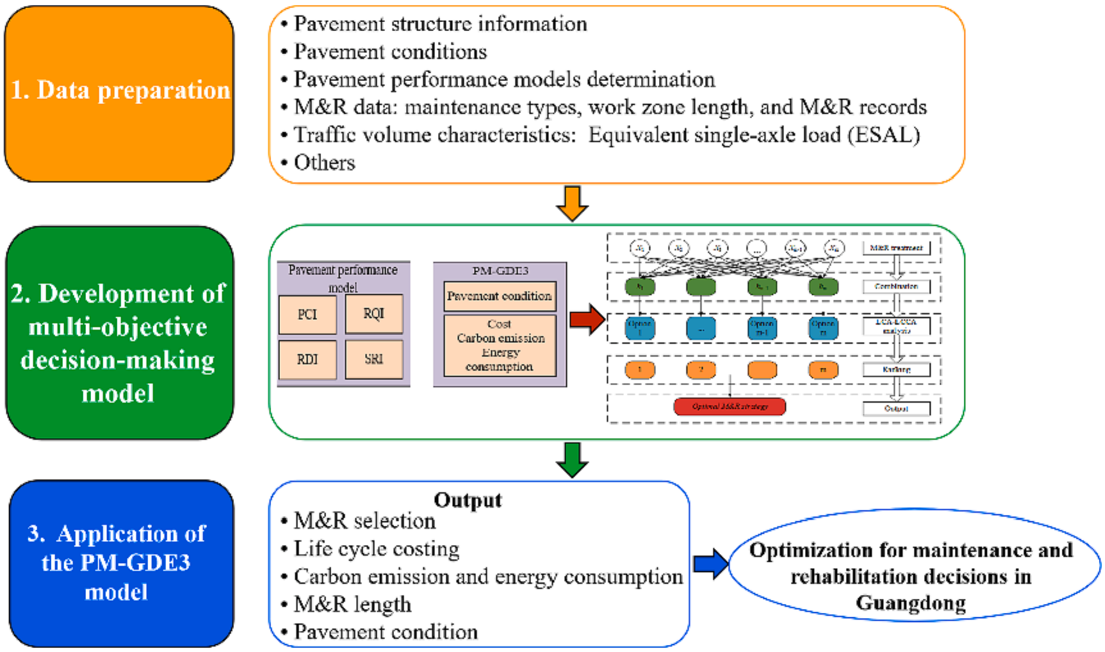

Fig. 1. Flowchart showing the organization of the methodology developed in this work.

population. In addition, determine whether the convergence condition and the preset maximum number of iterations have been reached or not and output the result if this is not the case.

3.2. Pavement condition evaluation indices

The pavement condition evaluation indices play a significant role in evaluating the pavement conditions and validity of the maintenance actions, which provides an approach to quantify the benefits. The pavement condition evaluation indices include, PCI, the rutting depth index (RDI), the riding quality index (RDI), and the skidding resistance index (SRI), which are the essential components of any pavement maintenance decision model [37].

In this study, a series of pavement condition prediction models, established in a previously published article [33], was applied to predict the pavement conditions on the basis of the previous trend in order to select a suitable maintenance action at the right time. The pavement condition prediction models were developed on the database of the Guangdong highways. The result shows that the prediction models have a precise prediction ability with an R^2 value of 91%. The integrated prediction models and the GDE3 algorithm were used to determine the optimal maintenance strategy.

3.3. Life cycle assessment and life cycle cost analysis

The Life cycke Assessment (LCA) approach, a simulation framework for assessing the environmental impacts of highway pavement during the pavement construction and maintenance stages, comprises the inventory analysis and impact assessment. The LCA method was mainly selected to estimate the environmental influence associated with the various pavement maintenance actions, including carbon emissions and energy consumption [38]. The Life cycle cost analysis (LCCA) method can be applied to evaluate the total costs required for the efficient usage of the pavement during the construction and maintenance stages [39]. In this study, the LCA and LCCA methods were integrated to assess the economic and environmental effects of the various maintenance schemes. According to the Asphalt Pavement Alliance (APA), the selection of analysis period generally is at least 30 years. Therefore, the analysis period determined in the research is 30 years [40].

To effectively evaluate and compare the energy consumption and carbon emissions of various asphalt pavement maintenance and rehabilitation strategies, it is crucial to select a consistent functional unit for assessing the environmental impacts. In this study, a 1 km single-lane pavement is defined as the functional unit of interest for this study. By calculating energy consumption and carbon emissions, the environmental load values for this functional unit are determined. Considering the large numerical values associated with energy consumption and carbon emissions for a 1 km pavement section, energy consumption is presented in units of megajoules (MJ) and carbon emissions in units of metric tons (tonnes) for ease of interpretation.Utilizing these equations enables the estimation of carbon emissions and energy consumption associated with different asphalt pavement maintenance and rehabilitation strategies [6,30,41], as shown in Eqs. (1a) to (3b).

Calculating the carbon emissions and energy consumption for asphalt pavement maintenance and rehabilitation activities involves several equations, which are used to estimate the emissions and energy use at different stages of the pavement life cycle. Here is an overview of the main calculations involved:

(1) Material production:

Carbon emissions (CE) for material production are calculated using the following equation:

$$CE_{material} = \sum_{i=1}^{n}(material_i \times EF_i) \tag{1a}$$

where *materiali* is the mass of material i used in the maintenance and rehabilitation activity, *n* is the number of material type, and *EFi* is the emission factor for materiali.

Energy consumption (EC) for material production can be calculated using a similar equation:

$$EC_{material} = \sum_{i=1}^{n}(material_i \times EF_{energy,i}) \tag{1b}$$

where *materiali* is the mass of material i used in the maintenance and rehabilitation activity, n is the number of material type, and *EFenergy,i* is the energy factor for materiali.

(2) Construction, maintenance, and rehabilitation:

Carbon emissions (CE) and energy consumption (EC) for the construction, maintenance, and rehabilitation activities are calculated based on the fuel consumption of the equipment used:

$$CE_{activity} = \sum_{i=1}^{n} \left(fuel_{consumption} \times EF_{fuel,i} \right) \tag{2a}$$

$$EC_{activity} = \sum_{i=1}^{n} \left(fuel_{consumption} \times EF_{energy,fuel,i} \right) \tag{2b}$$

where *fuelconsumption,i* is the fuel consumption of equipment i during the activity, *EFfuel,i* is the emission factor for the fuel used by equipment i, and *EFenergy,fuel,i* is the energy factor for the fuel used by equipment i.

(3) End-of-life disposal or recycling:

Similar equations can be used to calculate carbon emissions and energy consumption for end-of-life disposal or recycling processes, considering the material masses, transportation distances, and equipment fuel consumption involved.

Total carbon emissions and energy consumption:

Sum the carbon emissions and energy consumption for each phase of the pavement life cycle:

$$Total_{CE} = CE_{material} + CE_{activity} + CE_{end} \tag{3a}$$

$$Total_{EC} = EC_{material} + EC_{activity} + EC_{end} \tag{3b}$$

3.4. Maintenance and rehabilitation alternatives

The typical M&R actions applied to the pavement and the carbon emissions and energy consumption for asphalt pavement maintenance and rehabilitation activities have been summarized in Table 2. Due to the different quantities of asphalt maintenance and rehabilitation, Table 2 provides the approximate range of carbon emissions and energy consumption, and the specific values are calculated according to the maintenance model. According to the previously published articles [42,43], various maintenance and rehabilitation strategies have been proposed and evaluated in the literature. Based on these sources, a comprehensive set of alternatives that are relevant to our research context and compatible with the PM-GDE3 model has been selected. The main maintenance actions applied for highway pavement in Guangdong include milling and filling, micro-surfacing, ultra-thin friction course, and hot-in-place recycling [43]. The processes of milling and filling are relatively cheap and have low energy consumption and carbon emissions. Micro-surfacing is applied as the main preservation action for enabling a long service life of the road under heavy traffic. There are many advantages of applying the ultra-thin friction course, including rapid treatment of the existing pavement, excellent durability, and low emission. Hot in-place recycling is one of the rehabilitation treatments for the existing deteriorated asphalt pavement. Other maintenance technologies have been used less frequently [42]. In this study, the typically applied maintenance treatments were incorporated into the PM-GDE3 model, which tends to determine the preservation actions over rehabilitation treatments to keep the highway network in good condition.

Table 2
Summary of the available maintenance and rehabilitation treatments.

ID	M&R treatment	Category	Carbon emissions (kg/m^2)	Energy consumption (MJ/m^2)
1	Fog seal		5–18	100–280
2	Chip seal		8–20	150–350
3	Crack seal	Pavement	4–15	80–200
4	Thin asphalt surfacing	preservation	10–30	200–650
5	Ultra-thin friction course	treatments	15–35	260–690
6	Micro-surfacing		5–15	100–300
7	Hot in-place recycling		10–50	180–720
8	Cold in-place recycling		5–20	100–300
9	Mill & fill the top asphalt layer		50–90	600–1000
10	Mill and fill the top and middle asphalt layer	Rehabilitation	70–130	735–1250
11	Full depth asphalt layer reclamation		100–140	1100–1800

3.5. Establishment of PM-GDE3

The PM-GDE3 decision-making procedure consists of four main elements, namely, preparation, setting, solution, and sorting. The detailed process of the PM-GDE3 model operation is as follows:

(1) Preparation: The pavement maintenance requirement analysis is the first step in establishing the M&R strategy. The basic information on the highway network, such as the traffic conditions, the maintenance actions, the pavement structure, and the climate conditions, were collected and analyzed. The main objective of this step is to determine the sections which are under the normative maintenance standards, resulting in supplementing the basis for maintenance decision optimization.

(2) Setting: In this study, there are two types of optimization objectives that can be set in the PM-GDE3 model. The first objective includes the minimum M&R cost, carbon emissions, and energy consumption. The other considers the pavement condition indexes that exceed the minimum requirements during the analysis period, including PCI, RDI, RQI, and SRI. In terms of the first target, three objective functions were developed into the PM-GDE3 model, including the minimization of the maintenance cost, X(1), the minimization of carbon emissions, X(2), and the minimization of energy, X(3). These objective functions are expressed mathematically [44], as given in Eqs. (4) to (6). Different traffic lanes of a unit section were restricted to apply only one M&R treatment per year, and the various maintenance treatments for different lanes were set in the same segment. In the objective function of the pavement condition, the performance indices (RDI, PCI, RQI, and SRI) were higher than the defined lower threshold for each traffic lane. The performance index functions in this procedure are defined [44], as shown in Eqs. (7) to (10).

$$X_{1(\min)} = \sum_{i=1}^{Y} \sum_{i=1}^{n} \sum_{j=1}^{m} \sum_{k=1}^{z} T_i L_i C_i \tag{4}$$

$$X_{2(\min)} = \sum_{i=1}^{30} \sum_{i=1}^{n} \sum_{j=1}^{m} \sum_{k=1}^{3} T_i L_i P_i \tag{5}$$

$$X_{3(\min)} = \sum_{i=1}^{30} \sum_{i=1}^{n} \sum_{j=1}^{m} \sum_{k=1}^{3} T_i L_i E_i \tag{6}$$

$$PCI_i \geqslant 80 \tag{7}$$

$$RQI_i \geqslant 90 \tag{8}$$

$$RDI_i \geqslant 84 \tag{9}$$

$$SRI_i \geqslant 90 \tag{10}$$

where *Ti* is the type of treatment in the unit section, *Li* is the length of the lanes in the *i*th section, *Ci* is the maintenance cost of the selected treatment (in CNY), *Y* is the maintenance analysis period, *n* is the number of maintenance sections, *z* is the type of traffic lanes section, namely, the fast traffic lane, mid-traffic lane, and slow traffic lane, *Pi* is the unit carbon emissions of applied treatment, *Ei* is the unit carbon emissions of applied treatment, and *PCIi*, *RDIi*, *RQIi*, and *SQIi* are the performance indices in the *i*th segment.

(4) Solution: The GDE3 algorithm was implemented to solve the muti-objective problems. The first treatment was selected in each traffic

lane from the M&R actions database, shown in Table 2, according to the pavement performance condition. The performance indices, carbon emissions, cost, and energy consumption were calculated after selecting the treatment methods for different lanes, which were recorded into a logging module. Subsequently, various M&R actions were rapidly applied and sorted, and the calculated results fast ranking in the record section. In addition, the obviously weak strategies that cannot meet these objective functions were disused before the first four rounds of calculation. This process was done considering the total situation. The GDE3 algorithm differs from the typical multi-objective optimization algorithms in the selection process, where the former selects the prominent maintenance planning by a fast non-dominated sorting and crowding calculation, and the latter determines the individuals of the population by the fitness function. Furthermore, the GDE3 algorithm integrates an elite policy, which tends to remain the best planning for the offspring [9]. Finally, the GDE3 algorithm can maintain the diversity of the M&R options in such complex environments while also improving the calculation efficiency. The corresponding solution program is schematically shown in Fig. 2.

(4) Sorting: The main goal of this step is to select the optimal schedule from various strategies by a combined score which is a widely used approach to find the best solution. The principle of the method is ranking the solutions using the linear weighting of the selected metrics. The evaluated objects in this study are the various M&R strategies obtained by the PM-GDE3 model. The various M&R strategies were labeled as 1, 2, …, n. The values of the pavement performance index were normalized to the range of 0–10 by numerical adjustment [45], as shown in Eq. (11). The grades of the maintenance cost, carbon emissions, and energy consumption were scored from 0 to 20. The lowest maintenance cost scored 100, whereas the largest scored 0. Subsequently, the final score was calculated based on the weighted algebraic mean of each value [45], as presented in Eq. (12). The higher the final score, the more the corresponding solution meets the maintenance requirement of the M&R scheme decision-maker. The optimal M&R planning was selected from a series of output solutions by ranking all the alternatives according to the magnitude of the composite score (Fig. 3).

$$p_i = 10 - \frac{p_i - p_{i,\min}}{p_{i,\max} - p_{i,\min}} \tag{11}$$

$$F = \sum_{j=1}^{m} w_i p_i \tag{12}$$

where Pi is the values of the pavement performance index, Pi,min is the minimum values of the pavement performance index, Pi,max is the minimum values of the pavement performance index, F is the total score.

3.6. Selection of maintenance strategies using the PAVER tool

PAVERTM6.5 was applied for optimizing the pavement M&R strategy. Compared to the previous system of PAVER, the PAVERTM6.5 was integrated with a submodule that distributes M&R actions to the selected pavement [34,46]. The decision-making principle of PAVERTM6.5 involves the selection of a maintenance action based on the PCI thresholds. The working programming section of PAVERTM6.5 generates the M&R plans for different traffic lanes based on the M&R costs, the thresholds of PCI, and the limited funds.

4. Results

Fig. 4 illustrates the advancement in learning progress for the PM-GDE3 model. The abscissa delineates the progression of learning, wherein a single episode comprises a succession of states, actions, and rewards culminating in terminal states. The ordinate conveys the mean aggregate reward values for pavement performance and LCA-LCCA over a 30-year duration. These cumulative rewards exhibit a gradual ascent and ultimately plateau, signifying that the M&R policy has reached its maximum potential, and the optimal strategies have been ascertained. To demonstrate the preeminence of the PM-GDE3 model over the conventional PAVER tool, M&R approaches for the comprehensive pavement network were established employing both methodologies.

4.1. Maintenance length

Fig. 5 presents the total pavement maintenance length achieved using both the PM-GDE3 model and the PAVER tool. It was observed that, in comparison to the PAVER tool, PM-GDE3 favored preservation treatments over rehabilitation treatments, such as milling and resurfacing, ultra-thin overlay, and hot in-place rehabilitation, as illustrated in Fig. 5 (a). The M&R policy in PM-GDE3 is designed to prioritize preservation treatments over rehabilitation treatments. It is essential to note that the first year saw the highest annual maintenance cost and proportion, primarily due to the poor initial condition of the highway network pavement, which necessitated extensive maintenance and rehabilitation. Consequently, the overall condition of the highway

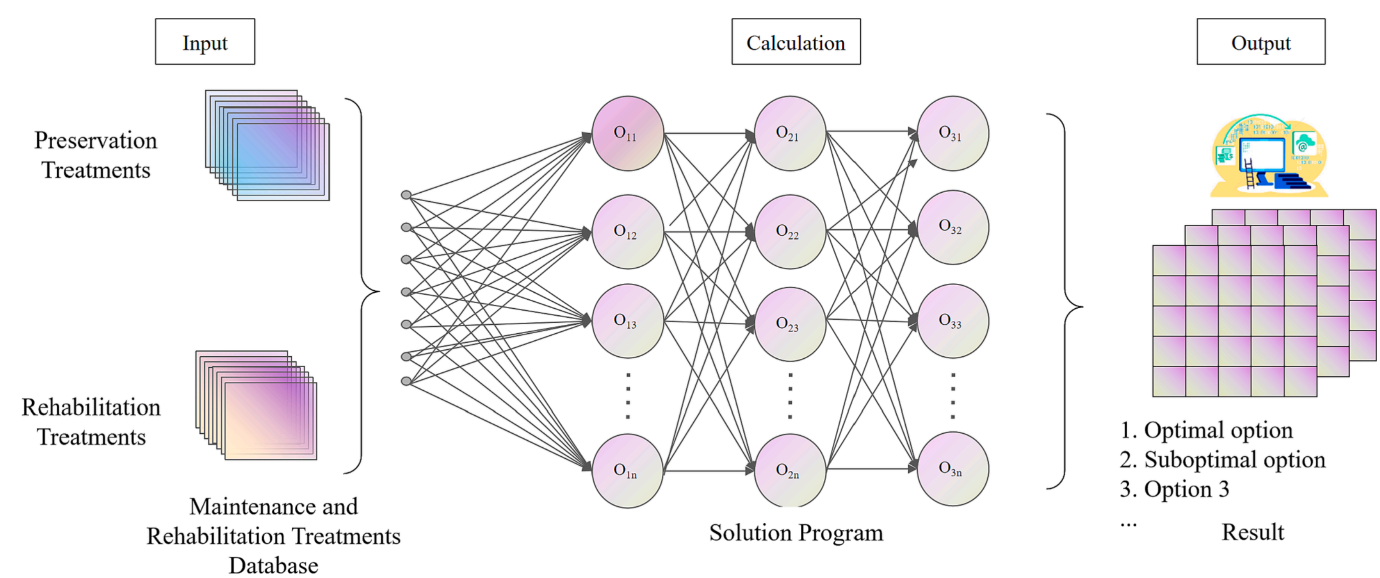

Fig. 2. A schematic of the GDE3 solving process.

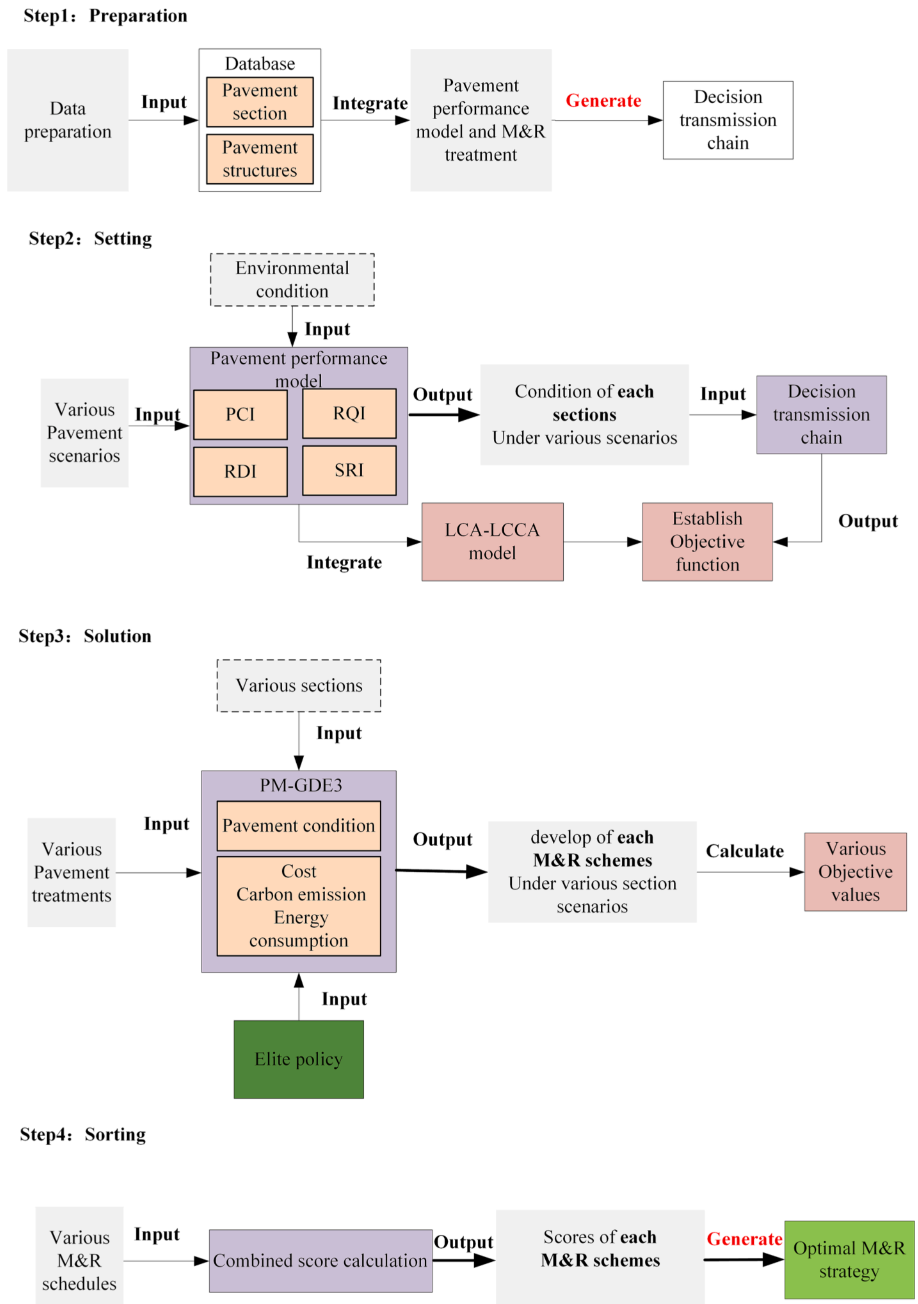

Fig. 3. A detailed schematic of the PM-GDE3 model.

network pavement improved significantly to an acceptable range.

As depicted in Fig. 5 (b), the total pavement maintenance length reached approximately 1963 km, nearly 2.1 times that of PM-GDE3, owing to the PAVER tool's maintenance strategy selection based on a fixed preservation framework. Additionally, the rehabilitation proportion of the entire M&R scheme increased considerably. Thus, the optimal maintenance strategy derived from PAVER was not the most suitable solution for the highway network, offering decision-makers fewer options compared to the PM-GDE3 model. Furthermore, the maintenance objective of the PM-GDE3 model was not to choose a maintenance strategy with the minimum maintenance length. Instead, it aimed to ensure that the pavement maintenance length remained within an acceptable range while recommending the use of preservation treatments. This approach results in a more balanced and efficient maintenance strategy, providing decision-makers with a broader range of options for maintaining and improving the condition of their highway network.

To elucidate the disparities in M&R approaches engendered by the two models, the temporal distribution of M&R treatments for both models is depicted in Fig. 6. The PM-GDE3 model manifests an elevated preservation treatment ratio; nonetheless, in contrast to the PAVER, it demonstrates a predilection for selecting fewer rehabilitations and an increased prevalence of preventive maintenance throughout a 30-year period. This accentuates the merits of preventive maintenance in mitigating the necessity for costly pavement rehabilitations.

4.2. Life cycle costing

Fig. 7 presents a comparison of the maintenance cost expenditure, carbon emission, and energy consumption obtained using the PM-GDE3 model and the PAVER tool. The optimal scheme of PAVER was notably higher than that of PM-GDE3, with the maintenance cost reaching 441.2

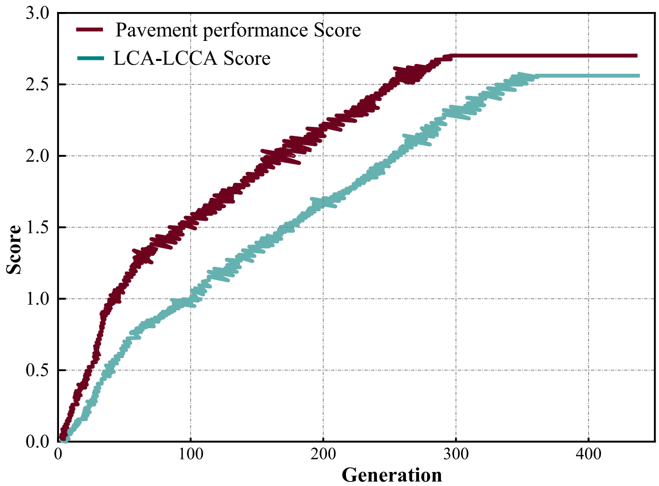

Fig. 4. Advancement in learning progress for the PM-GDE3 model.

million CNY during the maintenance period. The primary reason for this difference is that the PM-GDE3 model prioritizes determining the most appropriate preservation actions for this project over rehabilitation in order to maintain the large highway network in good usable condition, resulting in a dominant proportion of preservation.The preservation strategies employed on the highway included ultra-thin hot mix asphalt overlay, hot in-place rehabilitation overlay, micro-surfacing, and fog seal. Table 3 provides a summary of the costs associated with various maintenance actions. While the most economical actions were micro-surfacing and fog seal, other preservation strategies were relatively cost-competitive. In contrast, the cost of rehabilitation is several times that of preservation. Moreover, the PM-GDE3 model only tends to select the rehabilitation action when cost-effective preservation actions cannot maintain the road in usable conditions. Consequently, the PM-GDE3 model saved 171 million CNY compared to the PAVER tool, demonstrating its cost-effectiveness in managing pavement maintenance. By prioritizing preservation strategies and using rehabilitation only when necessary, the PM-GDE3 model not only lowers maintenance costs but also reduces the environmental impact of pavement maintenance. Decision-makers should consider the advantages of the PM-GDE3 model, as it offers a more efficient, cost-effective, and environmentally friendly approach to maintaining large highway networks.

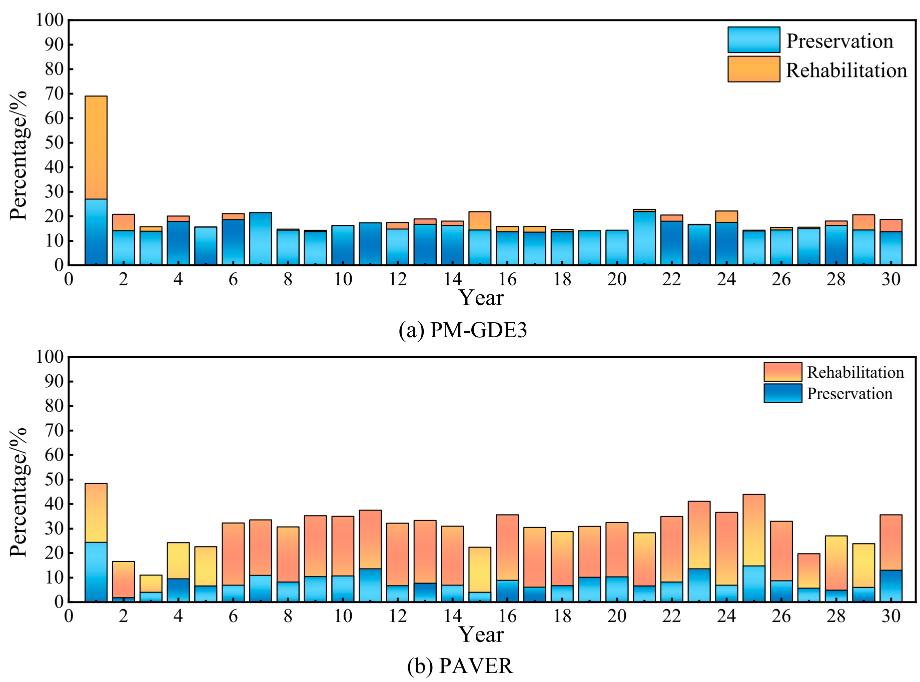

Fig. 5. The M&R proportion obtained from during the 30-year analysis period; (a) PM-GDE3; (b) PAVER.

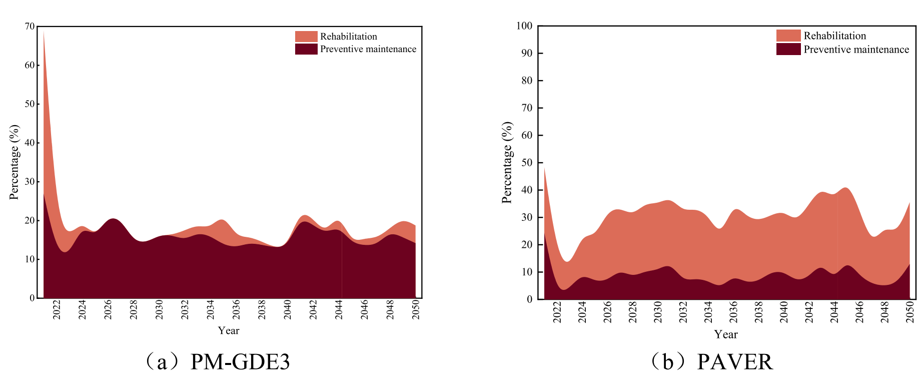

Fig. 6. The M&R proportion obtained from during the 30-year analysis period; (a) PM-GDE3; (b) PAVER.

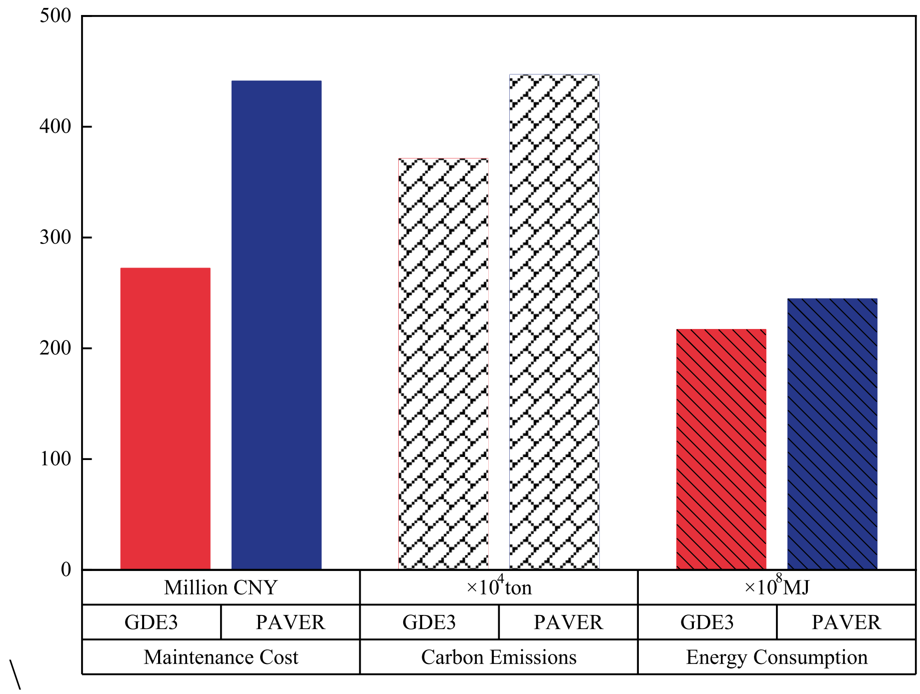

Fig. 7. The M&R cost, carbon emission, and energy consumption results during the 30-year analysis period.

Table 3
Summary of key metrics for different M&R strategies obtained by PM-GDE3.

Option ID	Cost (Million CNY)	Carbon emissions ($\times10^4$ton)	Energy consumption ($\times10^8$MJ)	PCI	RQI	RDI	SQI
<u>1</u>	<u>272</u>	<u>371.2</u>	<u>216.9</u>	<u>92</u>	<u>94</u>	<u>93</u>	<u>88</u>
2	283	371.3	219.2	91	95	92	90
3	313	392.1	199.8	90	92	91	86
4	369	428.2	251.7	92	94	92	89
5	418	444.7	240.5	91	88	89	88
6	421	465.3	230.1	89	90	91	89
7	495	559.1	271.5	90	91	90	87

The depiction infers that displacing the customary PAVER instrument with the PM-GDE3 model could engender considerable financial savings, with average savings across a 30-year duration amounting to approximately 171 million CNY for the comprehensive highway infrastructure. Concomitantly, this constitutes an estimated 26.59% reduction in the network expenditure necessitated by the PAVER apparatus.

4.3. Carbon emission and energy consumption

The carbon emission and energy consumption for the optimal maintenance schedules of PM-GDE3 and PAVER are compared in Fig. 8 (a) and Fig. 8 (b), respectively. With regard to carbon emissions, the PAVER tool generated the highest emissions, nearly 1.3 times that of the PM-GDE3 model, amounting to 4,469 kt. This significant difference can be attributed to the PAVER tool's preference for a high proportion of rehabilitation schedules in pavement maintenance. Rehabilitation actions such as milling, heating materials, and resurfacing contribute to large volumes of CO2 emissions.Similarly, a comparison of energy consumption between the PAVER and PM-GDE3 models reveals a consistent trend. The embodied energy consumption resulting from the PAVER tool is 1.12 times greater than that of the PM-GDE3 model, measuring 24.5 GJ and 21.7 GJ, respectively. The 2.8 GJ difference in energy consumption between the PAVER tool and PM-GDE3 model can be applied to a 3 km slow traffic lane by selecting the preservation option during the 30-year analysis period.

These findings suggest that adopting the PM-GDE3 model for pavement maintenance can lead to more sustainable and environmentally friendly strategies. By minimizing both carbon emissions and energy consumption, the PM-GDE3 model promotes responsible resource utilization and lessens the environmental impact of pavement maintenance. Consequently, decision-makers should consider the long-term benefits of utilizing the PM-GDE3 model when planning and executing pavement maintenance, as it offers a more efficient and eco-conscious approach.

4.4. Evaluation of the pavement condition

Fig. 9 illustrates the progression of pavement performance indicators (i.e., PCI, RDI, RQI, and SRI) after implementing the optimal maintenance strategy derived from both the PM-GDE3 model and the PAVER tool. As demonstrated in Fig. 9(a), the PM-GDE3 model successfully maintains the pavement condition at a consistently good usable level, with the PCI value remaining above 90 throughout the service life. In comparison, while the PAVER tool generates a similar PCI value, it experiences greater fluctuations. Regarding RDI, the PM-GDE3 model maintains values between 90 and 96, effectively keeping the rutting depth of the entire pavement network within an acceptable range. Although the PAVER tool exhibits a similar trend to the PM-GDE3 model, its RDI values are marginally smaller, indicating that the PM-GDE3 model delivers superior rutting resistance performance. Throughout the analysis period, the RQI value required by the PM-GDE3 model consistently stays above 90. Conversely, the PAVER model's RQI

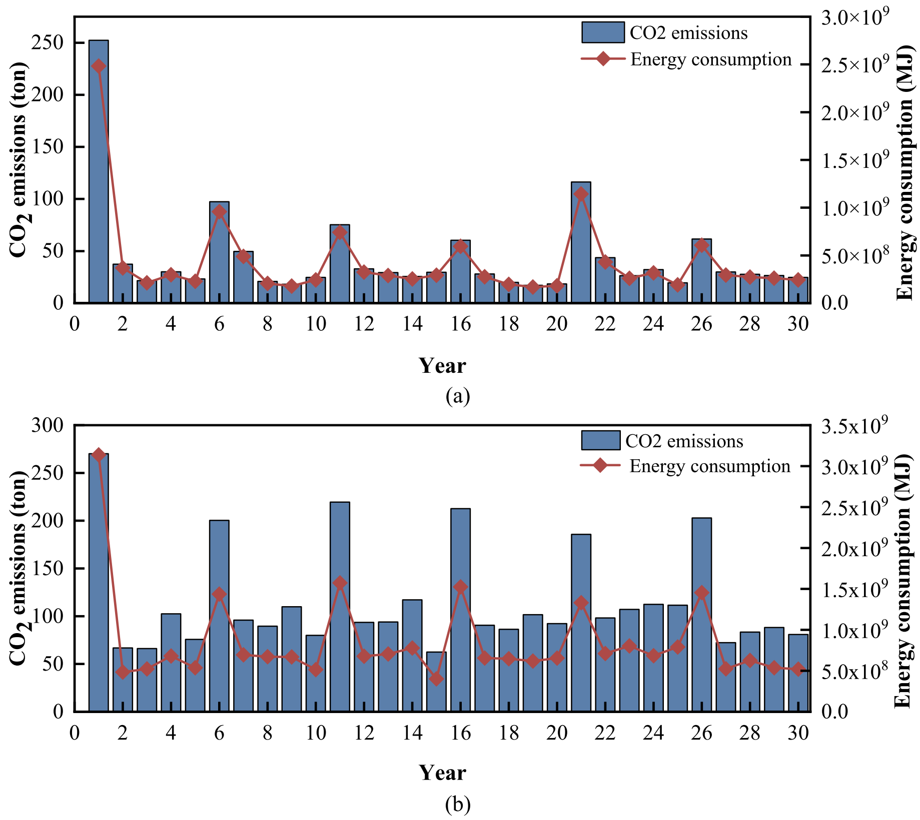

Fig. 8. Carbon emission and energy of treatments predicted results: (a) PM-GDE3; (b) PAVER.

is considerably worse, leading to increased user costs and diminished pavement safety. In terms of SRI, the PM-GDE3 model maintains an optimal range, while the PAVER tool presents the worst value with a scattered distribution.

In summary, the PM-GDE3 model demonstrates superior overall long-term pavement conditions for maintenance management optimization in Guangdong, offering more stable and consistent pavement performance indicators. This improved performance translates to better road safety, user satisfaction, and cost-efficiency, making the PM-GDE3 model a more favorable choice for pavement maintenance management in large-scale road networks.

Compared to the PAVER model, the PM-GDE3 model produces superior PCI results. As for the remaining pavement performance indicators (such as RDI, RQI, and SRI), they have also been explicitly optimized. Therefore, PM-GDE3 can optimize all four of these performance indicators. At the same time, PM-GDE3 strives to strike a balance between implementing reasonable M&R to improve pavement conditions and deferring M&R to reduce M&R expenditures, as shown in Fig. 5. Additionally, PM-GDE3 aims to maintain pavement conditions within an acceptable range, rather than sustaining them at optimal levels at the expense of significant costs and environmental degradation.

5. Discussion

Due to the satisfactory ability to evaluate the environmental and economic performance of different maintenance and repair methods for asphalt pavement, the combination of life cycle assessment (LCA) and life cycle cost analysis (LCCA) has become a widely used tool in road engineering. However, in the process of road maintenance management, due to the limitation of maintenance funds, it is urgent to use decision optimization tools to assist management departments to effectively utilize and allocate maintenance funds. Traditional pavement maintenance decision-making usually only considers single-objective optimization, such as maximizing pavement performance improvement or minimizing maintenance costs, taking the “most important” goal as the optimization goal, while ignoring secondary goals or converting them into conditional constraints (such as carbon emissions and energy consumption, asphalt pavement durability, and sustainability). However, there are often conflicts among multiple objectives, and only considering single-objective optimization decisions is obviously not comprehensive and cannot obtain the best maintenance plan. For example, Santos proposed a new adaptive hybrid genetic algorithm (AHGA) to solve the problem of road maintenance and repair (M&R) strategy selection, with the goal of minimizing total cost. The algorithm was applied to multiple actual cases to determine the best road maintenance and repair strategy, but it did not consider many decision factors, such as carbon emissions and energy consumption generated in maintenance and repair, durability of asphalt pavement after repair, etc. Yu et al. proposed a multi-objective optimization algorithm based on genetic algorithm to comprehensively consider pavement performance, cost, and environmental factors. Although the algorithm considered environmental factors, its interpretability was low, and it was difficult to understand and explain the specific execution process of the algorithm, lacking application to actual engineering. Therefore, there is a lack of pavement management models in road engineering that consider road performance, cost, and environmental factors to obtain comprehensive maintenance plans.

The research shows that the combination of GDE3 algorithm and LCA-LCCA to solve the maintenance and repair problem of large-scale highway asphalt pavement provides more comprehensive information for pavement engineering maintenance and planning decision-making, improves maintenance effectiveness and saves costs. Although most researchers focus on completing pavement maintenance and repair with minimal cost, we have demonstrated that environmental factors have important impacts on the condition of the road and maintenance strategies. Therefore, in solving the maintenance and repair optimization

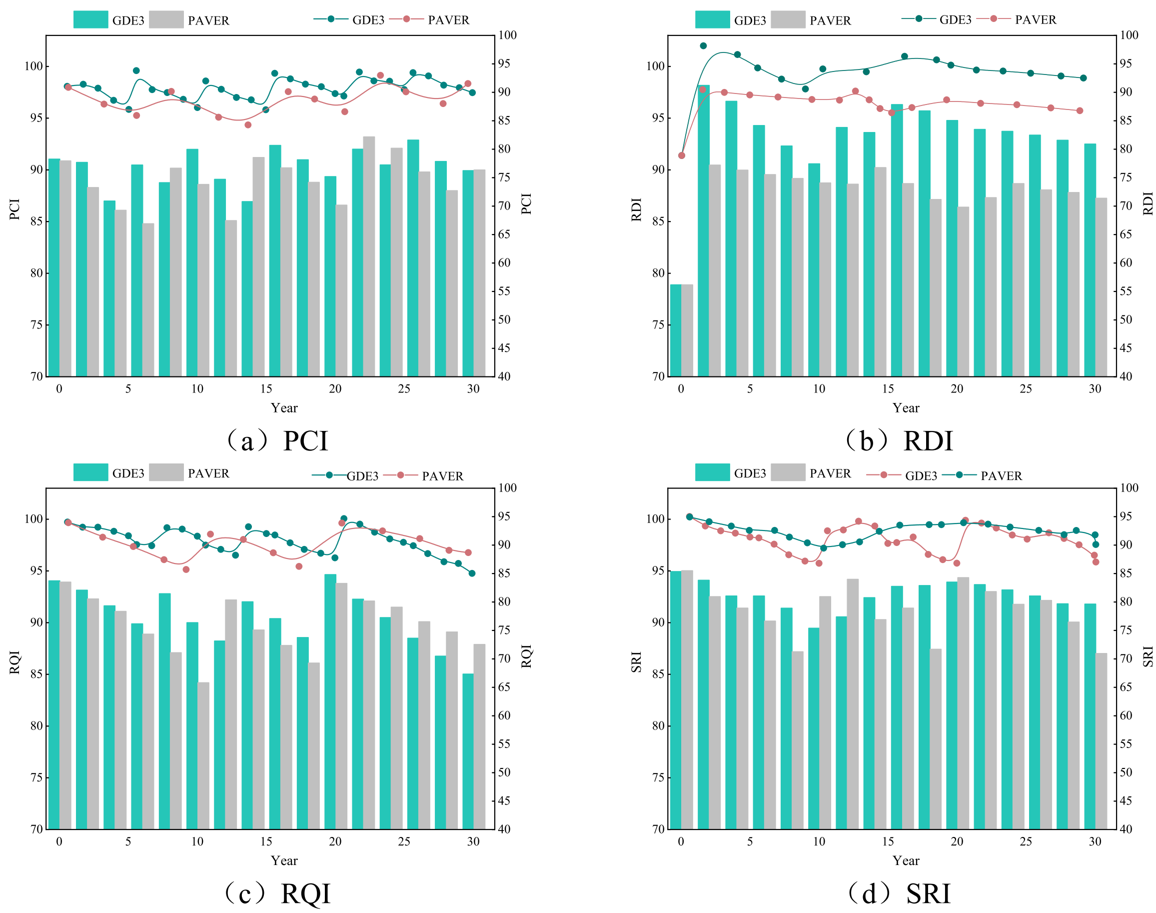

Fig. 9. Pavement performance metrics obtained by PM-GDE3 and PAVER.

problem of multi-lane highway asphalt pavement, we fully consider the impact of environmental factors, and thus the PM-GDE3 model is established to fully consider these factors.

The PM-GDE3 model in this paper is established as a multi-objective decision-making method in asphalt pavement maintenance management. To prove that the PM-GDE3 model is superior to the traditional PAVER tool, the selected M&R treatments, maintenance proportion, M&R length, the pavement conditions after various treatments, the cost-effectiveness of the strategy, and the environmental benefits of the optimal maintenance alternatives for the entire Guangshen highway were compared based on both models. The pavement conditions of PM-GDE3 were significantly better than those of the PAVER tool. Based on the PM-GDE3 model, the PCI, RDI, RQI, and SQI of the entire pavement sections were generally at an excellent level during the 30-year analysis period. However, the results of this study were only verified by a small amount of field data, lacking verification from a large amount of field experiments, which requires further research.

Although existing literature has focused on the energy consumption and carbon emissions in the maintenance and repair process of asphalt pavement, we quantified the energy consumption and carbon emissions of different maintenance and repair schemes for asphalt pavement, which is particularly important in achieving low-carbon road engineering. Previous studies lacked a quantitative analysis of carbon emissions and energy consumption in the construction and maintenance of large-scale highway networks. While the environmental impact of asphalt pavement construction and maintenance has been debated for a long time, most studies have not quantified the carbon emissions and energy consumption in these processes. In this paper, we used the PM-GDE3 model, a multi-objective decision-making model, to minimize M&R costs while maximizing the benefits of energy consumption reduction and carbon emission reduction. We prioritized the benefits of energy consumption and carbon emission reduction when formulating the final M&R strategy, and analyzed the energy consumption and carbon emissions of different M&R strategies, and compared the effects of the PM-GDE3 model and the traditional PAVER tool on energy consumption and carbon emissions. We demonstrated the advanced nature of the PM-GDE3 model by using specific energy consumption and carbon emissions data, providing ideas and basis for further achieving low-carbon asphalt pavement. Excitingly, the PM-GDE3 model can formulate more environmentally friendly and sustainable M&R strategies, reducing carbon emissions and energy consumption in the highway maintenance and repair process, thus better protecting the environment and promoting sustainable development.

In summary, this research has provided a practical solution to the actual problems in road engineering, which can effectively solve the maintenance and repair problems of large-scale highway asphalt pavement, improve the efficiency of highway use, maintenance cost-effectiveness, and environmental sustainability.

6. Conclusions

In this study, an efficient and improved M&R decision-making model (PM-GDE3) was proposed to achieve the optimal environmental, economic, and effective pavement maintenance program design for highways in China. A widely used maintenance model (i.e., PAVER) was selected for comparison with the PM-GDE3 model. The economic and environmental benefits of pavement preservation alternatives were analyzed for the different traffic lanes. The main conclusions of this study are as follows:

1. The outstanding performance of the PM-GDE3 model was mainly attributed to its mutation and crossover operators, including three individuals. The optimal maintenance strategies obtained from the PM-GDE3 model are more diverse and extensive than those of the PAVER tool, providing engineers with more schedules.
2. There was a significant difference in the maintenance cost, energy consumption, and carbon emission between the PM-GDE3 model and the PAVER tool. The schedules generated by the PM-GDE3 model saved at least 169 million CNY compared to PAVER. PM-GDE3 model saved about 16.9% of carbon emissions and 11.6% of energy consumption for as long as 30 service years compared to the PAVER model, which was equal to 4469 kt and 2.8GJ, respectively.
3. According to the above results, the PM-GDE3 model is applied to formulate the M&R plan for the highway network, and the durability of pavement structure is in a stable level during the 30-year maintenance period which the indexes such as PCI, RDI, RQI and SRI are at a better level. The pavement performance is maintained in a better state during the maintenance planning period.
4. The multi-objective optimization method is applied to the pavement maintenance decision, and the maintenance plan is selected according to the actual pavement conditions and the key maintenance decision of the pavement is constructed. Compared with the traditional pavement maintenance model, the best maintenance scheme proposed by PM-GDE3 maximizes the economic benefits and environmental benefits of maintenance.
5. Taking Guangzhou-Shenzhen Expressway as the long-term research object, the multi-objective maintenance decision-making dynamic model is established. The PM-GDE3 model solves the specific maintenance plan of Guangzhou-Shenzhen Expressway for 30 years, which can maintain the sustainability performance of asphalt pavement with the minimum M&R cost, carbon emissions and energy consumption during the maintenance period. The validity of the PM-GDE3 model is verified in a short time.

Since only limited case study was selected for analysis in this study, the accuracy of the proposed model requires further validation. In this project, the deterioration of the semi-rigid base layer was not taken into account because it was in an acceptable condition over the analysis period considered in this study. Thus, in future work, a larger number of highways will be selected to estimate the proposed model validity, which improves the practicality of the PM-GDE3 model. In addition, the performance prediction model of the semi-rigid layer will be taken into consideration in the model.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

The authors sincerely acknowledge the funding support from National Science Foundation of China (NSFC 51278203) and Natural Science Fund of Guangdong Province (2019A1515011965).

References

[1] Y. Liu, Y. Wang, D. Li, Estimation and uncertainty analysis on carbon dioxide emissions from construction phase of real highway projects in China, J. Clean. Prod. 144 (2017) 337–346, https://doi.org/10.1016/j.jclepro.2017.01.015.

[2] H. Gong, B. Huang, X. Shu, S. Udeh, Local calibration of the fatigue cracking models in the Mechanistic-Empirical Pavement Design Guide for Tennessee, Road Mater. Pave. Des. 18 (2017) 130–138, https://doi.org/10.1080/14680629.2017.1329868.

[3] M. Lanotte, M.E. Kutay, S.W. Haider, G.K. Musunuru, New calibration approach to improve Pavement ME Design thermal cracking prediction: mixture-specific coefficients – the Michigan case study, Road Mater. Pavem. Des. 21 (2020) 1859–1871, https://doi.org/10.1080/14680629.2019.1570863.

[4] K. Golabi, R.B. Kulkarni, G.B. Way, A statewide pavement management system, Interfaces 12 (1982) 5–21, https://doi.org/10.1287/inte.12.6.5.

[5] A. Medury, S. Madanat, Simultaneous network optimization approach for pavement management systems, J. Infrastruct. Syst. 20 (2014) 04014010, https://doi.org/10.1061/(ASCE)IS.1943-555X.0000149.

[6] C. Han, T. Ma, S. Chen, Asphalt pavement maintenance plans intelligent decision model based on reinforcement learning algorithm, Constr. Build. Mater. 299 (2021), 124278, https://doi.org/10.1016/j.conbuildmat.2021.124278.

[7] B. Yu, X. Gu, F. Ni, R. Guo, Multi-objective optimization for asphalt pavement maintenance plans at project level: Integrating performance, cost and environment, Transp. Res. Part D: Transp. Environ. 41 (2015) 64–74, https://doi.org/10.1016/j.trd.2015.09.016.

[8] S.P. Hamdi, A.G. Hadiwardoyo, P. Correia, Pereira, pavement maintenance optimization strategies for national road network in indonesia applying genetic algorithm, Procedia Eng. 210 (2017) 253–260, https://doi.org/10.1016/j.proeng.2017.11.074.

[9] S. Li, Z. Wang, X. Wu, Z. Zeng, P. Shen, C. Lai, A novel spatial optimization approach for the cost-effectiveness improvement of LID practices based on SWMM-FTC, J. Environ. Manage. 307 (2022), 114574, https://doi.org/10.1016/j.jenvman.2022.114574.

[10] J. Santos, A. Ferreira, G. Flintsch, An adaptive hybrid genetic algorithm for pavement management, Int. J. Pavement Eng. 20 (2019) 266–286, https://doi.org/10.1080/10298436.2017.1293260.

[11] M.R. Heidari, G. Heravi, A.N. Esmaeeli, Integrating life-cycle assessment and life-cycle cost analysis to select sustainable pavement: A probabilistic model using managerial flexibilities, J. Clean. Prod. 254 (2020), 120046, https://doi.org/10.1016/j.jclepro.2020.120046.

[12] J. Lee, S. Madanat, Jointly optimal policies for pavement maintenance, resurfacing and reconstruction, EURO J. Transport. Logistics 4 (2015) 75–95, https://doi.org/10.1007/s13676-014-0065-1.

[13] B. Leite, A.O.S. da Costa, E.F. da Costa Junior, Multi-objective optimization of adiabatic styrene reactors using Generalized Differential Evolution 3 (GDE3), Chem. Eng. Sci. 265 (2023), 118196, https://doi.org/10.1016/j.ces.2022.118196.

[14] D.E.C. Vargas, A.C.C. Lemonge, H.J.C. Barbosa, H.S. Bernardino, Solving multi-objective structural optimization problems using GDE3 and NSGA-II with reference points, Eng. Struct. 239 (2021), 112187, https://doi.org/10.1016/j.engstruct.2021.112187.

[15] S. Kukkonen, J. Lampinen, GDE3: The third evolution step of generalized differential evolution, in: IEEE, 2005, pp. 443–450.

[16] S. Kukkonen, J. Lampinen, Performance assessment of generalized differential evolution 3 (GDE3) with a given set of problems, in: IEEE, 2007, pp. 3593–3600.

[17] A. Deb, J.S. Roy, B. Gupta, Performance comparison of differential evolution, particle swarm optimization and genetic algorithm in the design of circularly polarized microstrip antennas, IEEE Trans. Antennas Propagat. 62 (2014) 3920–3928, https://doi.org/10.1109/TAP.2014.2322880.

[18] A.W. Iorio, X. Li, Solving rotated multi-objective optimization problems using differential evolution, in: G.I. Webb, X. Yu (Eds.), AI 2004: Advances in artificial intelligence, Springer Berlin Heidelberg, Berlin, Heidelberg, 2004, pp. 861–872, https://doi.org/10.1007/978-3-540-30549-1_74.

[19] K.V. Price, Differential evolution: a fast and simple numerical optimizer, in: Proceedings of North American Fuzzy Information Processing, IEEE, 1996: pp. 524–527.

[20] K. Quresh, S. Rahnamayan, Y. He, R. Liscano, Enhancing LQR Controller Using Optimized Real-time System by GDE3 and NSGA-II Algorithms and Comparing with Conventional Method, in: 2019 IEEE Congress on Evolutionary Computation (CEC), IEEE, Wellington, New Zealand, 2019: pp. 2074–2081. https://doi.org/10.1109/CEC.2019.8789894.

[21] J. Santos, A. Ferreira, G. Flintsch, A multi-objective optimization-based pavement management decision-support system for enhancing pavement sustainability, J. Clean. Prod. 164 (2017) 1380–1393, https://doi.org/10.1016/j.jclepro.2017.07.027.

[22] C. Pilson, W.R. Hudson, V. Anderson, Multiobjective optimization in pavement management by using genetic algorithms and efficient surfaces, Transp. Res. Rec. 1655 (1999) 42–48.

[23] T.F. Fwa, W.T. Chan, K.Z. Hoque, Multiobjective optimization for pavement maintenance programming, J. Transp. Eng. 126 (2000) 367–374.

[24] L. Yao, Z. Leng, J. Jiang, F. Ni, Large-scale maintenance and rehabilitation optimization for multi-lane highway asphalt pavement: a reinforcement learning approach, IEEE Trans. Intell. Transport. Syst. 23 (2022) 22094–22105, https://doi.org/10.1109/TITS.2022.3161689.

[25] X. Mao, H. Jia, S.L. Yu, Assessing the ecological benefits of aggregate LID-BMPs through modelling, Ecol. Model. 353 (2017) 139–149, https://doi.org/10.1016/j.ecolmodel.2016.10.018.

[26] G. Liu, L. Chen, Z. Shen, Y. Xiao, G. Wei, A fast and robust simulation-optimization methodology for stormwater quality management, J. Hydrol. 576 (2019) 520–527, https://doi.org/10.1016/j.jhydrol.2019.06.073.

[27] H. Yeo, Y. Yoon, S. Madanat, Algorithms for bottom-up maintenance optimisation for heterogeneous infrastructure systems, Struct. Infrastruct. Eng. 9 (2013) 317–328, https://doi.org/10.1080/15732479.2012.657649.

[28] L. Gao, Z. Zhang, Robust optimization for managing pavement maintenance and rehabilitation, Transp. Res. Rec. 2084 (2008) 55–61, https://doi.org/10.3141/2084-07.
[29] H. Zhang, G.A. Keoleian, M.D. Lepech, A. Kendall, Life-cycle optimization of pavement overlay systems, J. Infrastruct. Syst. 16 (2010) 310–322, https://doi.org/10.1061/(ASCE)IS.1943-555X.0000042.
[30] B. Yu, Q. Lu, J. Xu, An improved pavement maintenance optimization methodology: Integrating LCA and LCCA, Transp. Res. A Policy Pract. 55 (2013) 1–11, https://doi.org/10.1016/j.tra.2013.07.004.
[31] Department of transport of Guangdong Province, Department of transport of Guangdong Province, 2021. China. http://www.http://td.gd.gov.cn/, (2021).
[32] Y. Liu, Y. Wang, D. Li, F. Feng, Q. Yu, S. Xue, Identification of the potential for carbon dioxide emissions reduction from highway maintenance projects using life cycle assessment: A case in China, J. Clean. Prod. 219 (2019) 743–752, https://doi.org/10.1016/j.jclepro.2019.02.081.
[33] R. Liao, Study on Evaluation and Prediction of Pavement Performance Based on Cloud Model and XGBoost, South China University of Technology, 2021.
[34] X. Peng, Study on Free Asphalt Pavement Maintenance Strategy based on Pavement Management System, South China University of Technology, 2014.
[35] B. Yu, Q. Lu, Life cycle assessment of pavement: methodology and case study, Transp. Res. Part D: Transp. Environ. 17 (2012) 380–388.
[36] C.-L. Huang, N.-S. Hsu, H.-J. Liu, Y.-H. Huang, Optimization of low impact development layout designs for megacity flood mitigation, J. Hydrol. 564 (2018) 542–558.
[37] S. Dong, P. Hao, S.L. Tighe, A diagnostic method for evaluating the condition index of cement-stabilised base using T-S fuzzy neural network, Int. J. Pavement Eng. 20 (2019) 1140–1153, https://doi.org/10.1080/10298436.2017.1394097.
[38] Y. Huang, R. Bird, O. Heidrich, Development of a life cycle assessment tool for construction and maintenance of asphalt pavements, J. Clean. Prod. 17 (2009) 283–296.
[39] P. Babashamsi, N.I.M. Yusoff, H. Ceylan, N.G.M. Nor, H.S. Jenatabadi, Evaluation of pavement life cycle cost analysis: Review and analysis, Int. J. Pavement Res. Technol. 9 (2016) 241–254.
[40] A.P. Alliance, Pavement type selection, Asphalt Pavem. (2010).
[41] L. Zhang, L. Fu, W. Gu, Y. Ouyang, Y. Hu, A general iterative approach for the system-level joint optimization of pavement maintenance, rehabilitation, and reconstruction planning, Transp. Res. B Methodol. 105 (2017) 378–400, https://doi.org/10.1016/j.trb.2017.09.014.
[42] Y. Ma, Evaluation of Guangdong Province Highway pavement maintenance based on DEA and effective Pavement Maintenance Strategy Research, South China Univesity of Technology, 2017.
[43] S. Li, Investigation on Decision-Making for Pavement Maintenance and Rehabilitation of A County Road Networks, South China University of Technology, 2017.
[44] S. Xie, Research on Evaluation Method of Maintenance Benefit of Highway Asphalt Pavement, Southeast University, 2016.
[45] H. Li, A. Saboori, X. Cao, Information synthesis and preliminary case study for life cycle assessment of reflective coatings for cool pavements, Int. J. Transp. Sci. Technol. 5 (2016) 38–46.
[46] Q. Qian, Research of sustainable pavement maintenance strategy, South China University of Technology, n.d.