International Journal of Engineering

Journal Homepage: www.ije.ir

Pavement Maintenance Management Using Multi-objective Optimization: (Case Study: Wasit Governorate-Iraq)

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PAPER INFO

Paper history:
Received: 16 March 2020
Received in revised form: 16 June 2020
Accepted 21 July 2020

Keywords:
Genetic Algorithms
Maintenance
Optimization
Pavement
Roadway

A B S T R A C T

Limited resources and budget are the most important problem facing the road management sector; therefore, apportionment of maintenance and rehabilitation (M&R) requirements and priorities at the right time and logical are the most significant factors . Roadway will request continuous (M&R) works to avoid deterioration result from repetitive vehicle weight as well as other factors such as environmental factors. Whether, with the allocation budget that was allocated for roadway maintenance work; there is a necessity to efficiently used the obtainable funding. To execute this, a systematic approach for planning M-and-R process to reach optimum the benefits from roadway segment and minimize necessary funding and costs to repeat the pavement into first state. This process defined as the pavement maintenance management system (PMMS); thus, approach would enable agency to allotted funds, labors, equipment and other resources, most efficiently .This paper demonstrates the applying process of the maintenance program according to the genetic algorithm optimization. The aim of it was to obtain the optimal maintenance strategy alternative percent to reach best values for service life extended as well as increasing the pavement condition index (PCI) along with a specific budget that is not sufficient to restore the whole pavement to its previous state. After applying this program, it was found that it gives the road an additional service life (1.2 years), and at the same time it gives an increase in PCI value (3.8%), taking into consideration the limited resources allocated for maintenance.

doi: *10.5829/ije.2020.33.11b.05*

NOMENCLATURE

Xi	Value between 0 and 1 represent the percent of segment of roadway under treatments	*i =*	Chosen segment number
n	Number of road segments	*j =*	Type of maintenance strategy options
Ci	Percent of funding or budget	*m =*	Total number of pavement maintenance options
UI	Useful service life extended index	X_{ij}	Value between 0 and 1 represent the percent of segment of roadway under treatments.
le	Maintenance options life extended in year	d_i	PCI rating for each road segment
mle	Maximum maintenance options life extended in year, usually taken 10 years	*Bl*	Budget allocated to road

1. INTRODUCTION

Appropriate management, study and planning are effective factors in maintaining the level of service provided by infrastructure projects and preventing possible deterioration through maintenance of the integrity of such projects. Neglect or misuse and mismanagement of these public services can result in additional expenses and subversive alternatives as well as significant failures [1].

Decision-makers (DMs) need mathematical solutions and process research models to find appropriate

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Please cite this article as: A. K. Shadhar, A. M. Raoof Mahjoob, Pavement Maintenance Management Using Multi-Objective Optimization: Wasit Governorate-Iraq as a Case Study, International Journal of Engineering (IJE), IJE TRANSACTIONS B: Applications Vol. 33, No. 11, (November 2020) 2155-2161

decisions in case of a number of conflicting goals that need to deal effectively and ideally to reach the optimal decision. As an example of this case when there is a desire to improve the level of performance of a particular project at the same time there are financial constraints through limited budget or lack of financial allocations available for maintenance work. Therefore, there is a need for a multi-objective decision support system (MODSS) to improve the effective use of available resources and to create a distinct cost-benefit ratio.

It is necessary to understand the nature of the infrastructure projects and the history of maintenance of its parts and study the mechanism of degradation of the project, as the process of optimal decision-making requires knowledge of the problem and determine its variables and what are the most important constraints that may hinder the achievement of the appropriate decision which in turn leads to the creation of an effective maintenance and rehabilitation program for the project under study.

In fact, the current state of the project and its future development are determinants of the effectiveness of any (DSS) [2]. In this paper, performance will be increased through benefiting from expertise in pavement engineering as well as information and knowledge available from other areas such as management science, decision support systems, mathematical modeling and artificial intelligence. Furthermore, this research is part of the study of the benefits of using multi-objective systems in the management of pavement maintenance.

2. RESEARCH METHODOLOGY

The methodology for this research is:

- Provides a brief review of existing optimization technique throughout related literature review.
- Define Genetic Algorithm technique.
- Determine project deterioration rate from data provided by bridges directorate of Wasit.
- Define optimization objective functions and constraints of the roadway.
- Applying the optimization tool for cost and the stable rehabilitation or maintenance required using Genetic Algorithm technique.

3. RELATED LITERATURE

In the field of pavement management, there are several mathematical models using step to reach optimum solution known as optimization technique, and usually used are linear programming (LP), dynamic programming (DP), integer programming (IP), nonlinear, and Multi-objective optimization (MO) [3]. Often, optimal solutions within the synthesis of the infrastructure management problem determination and formulation caused from a well defined variables of mathematical models in optimization field.

Linear programming (LP) in road network domain commonly involves dividing the road into groups of pavement segment that have similar features, such as road class, pavement condition rating, traffic load road dimensions, distress type, etc. Based on this, M&R treatments varying and a resource allocation problem is formulated in order to find the optimal distribution of resources for the pavement groups under study. Accordingly, LP models are relatively manageable and allow users to test its modeling though perform sensitivity analyses for the output data and input factors [4].

In domain in which LP fails, the integer programming (IP) tactic prosper. IP models can provide precise facts regarding M&R strategy activities scheduling and individual segment selections to reach the optimum rating of the roadway network However, IP models need to more calculation step, essentially when performing on huge networks [5].

Even for single-objective functions, the scheduling and planning model that has integer solution or resolving variables is a nondeterministic polynomial time (NP)–difficult problem [6]. Furthermore, dynamic programming (DP) can be used to solve separated problems having a clear construction and imbrication secondary problems. This means that the issue formulated should be solvable consecutive, and ingredient of the most favorable solution should also smooth the solving of sub-problem [7]. Else, DP is often used for searching the circumstance of uncertainty in defining the best M&R strategy in infrastructure [8-10]. Finally, nonlinear programming models usually have their objective and at sometimes one of their restriction formulated as nonlinear (curvilinear) [11]. Many studies that have used nonlinear programming proposed that it is more reflexive of the allocation of the chosen input variables, particularly for variables concerning with roadway performance [12, 13].

Thorough knowledge and survey of related study in the literature discover a high number of works using genetic algorithms (GAs) for solving infrastructure maintenance resource distribution problems as well as in structural building [14, 15].

Multi-objective optimization transacts with more complex scenarios where DMs need to reconcile between multiple and often incompatible goals with each other. In fact, systems optimized taking into account a single feature might not perform efficiently with consideration to other systems, and optimizing problems according to multiple concordant features becomes major requirements to achieve the best results. GA built in solving the multi-objective optimization [16].

4. PAVEMENT CONDITION INDEX CALCULATION

The rating of roadway is specified from a correlation that display roadway rating as a result of the PCI value calculation. Table 1 presents the PCI ratings limits.

When explaining data that was collected from field survey and visual inspection for road condition, three varied type of the collected data must have concerned: the traffic density, the type, density and severity of distress at survey time and at last the evolution of road deterioration. The PCI value presents a general conception of the pavement state and the nature of the work that will be wanted to maintain the pavement. Pavements at surface layer are more potential to require a simple repair and minor maintenance, while the lower layers of road are more suitable to be nomination for essential rehabilitation or reconstruction (Shahin 2005).

There are two methods for calculating PCI, which are the manual method, it depends on the use of equations and curves, while the second method uses the PAVER software.

5. MAINTENANCE STRATEGY ALTERNATIVE

The objective was addressed to this study is to select the optimum pavement maintenance strategy. This selection has been made based on maximum benefit to cost ratio. All the benefits and costs have been converted to monetary terms. Functional benefits have been estimated using PCI increase due to a maintenance treatment which is the key component of this study. Data [17], regarding the life extension of the pavement due to various treatments and their unit costs have been obtained from airport cooperative research program (ACRP), and it is shown in Table 2.

The PCI increase data has been obtained from a previous study. All treatments are applied over the whole area as surface treatment except the spray patching. It is assumed that 50% area should be patched where patching is required.

6. CASE STUDY

The proposed methodology aims to be implemented on any type of road. As an application, a case study is prepared to identify the best strategy option that will be done for the major road which connects the commercial capital of Iraq; Baghdad city with eastern south Kut city as well as with other major cities. This road is a significant entrance of south Iraq capital for transportation of people and goods as well. The percentage of total vehicles represents the big amount of heavy vehicles movement on this road.

TABLE 1. PCI rating scale

PCI Range	Rating Scale
71-100	Good
56-70	Fair
40-55	Poor
25-39	Very Poor
0-24	Failed

TABLE 2. Unit cost and life extension of different maintenance strategy [17]

Alternative	Maintenance	Unit Cost ($/M²)	Life Extension (Years)	PCI Rise
1	Crack Treatment	1.75	3	5
2	Patching	6.5	4	5
3	Slurry Seal	3.5	5	30
4	Thin Overlay	8.5	10	35

Data collected from bridges directorate of Wasit, is discussed in Table 3.

According to official source the budget allocated to road *Bl* for each last two years was equal to $15*10^8$ DI, and this funding must be distributed to all roadway segment according to priority determinate through optimization process with genetic algorithms.

7. GENETIC ALGORITHM FORMULATION

The variables of decision model are exemplifying in GAs by a string framework comparable to the chromosomes in natural growth. The decision variables relate to the choice of pavement sections chosen for maintenance. A suitable string framework is one that be formed of one cell for each pavement section as shown in Figures 1(a) and 1(b) [17]. Therefore, the number of roadway segments of the road chosen should be equal to number of cells (total length of the string framework).

TABLE 3. PCI rating

Segment NO.	1	2	3	4
PCI	31	12	36	57

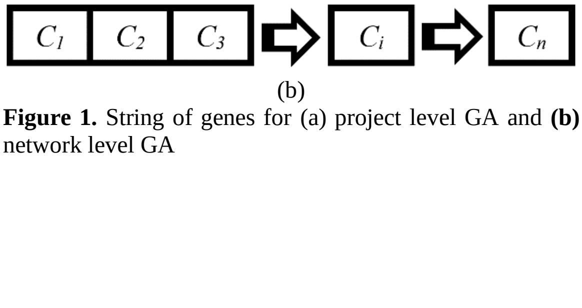

Figure 1. String of genes for (a) project level GA and **(b)** network level GA

The decision taken about value of each cell gives the percent of the road segment needed for maintenance that the cell represents.

The decision variables are plainly represented the percentage shares of funding allotment for the roadway. As shown in Figure 1(b). The genes values C1 represent percent of funding or budget (cost of treatment) that will be allotment for each X1 segment and so on. The following figure (Figure 2) shows the process flow chart for the genetic algorithm optimization [18].

8. USEFUL SERVICE LIFE EXTENDED INDEX

The best way to prioritize road repair is by determining the added service life that will be obtained through the adoption of the proposed maintenance option, provided that it does not conflict with the budget limits and the specific financial allocation.

The added service life coefficient (UI) will be adopted which can be obtained from the following equation:

$$\text{UI} = \frac{le}{mle} \quad (1)$$

where, UI is useful service life extended index; le is each maintenance options life extended in a year (Table 2). Also, mle is maximum maintenance options life extended in a year, usually taken 10.

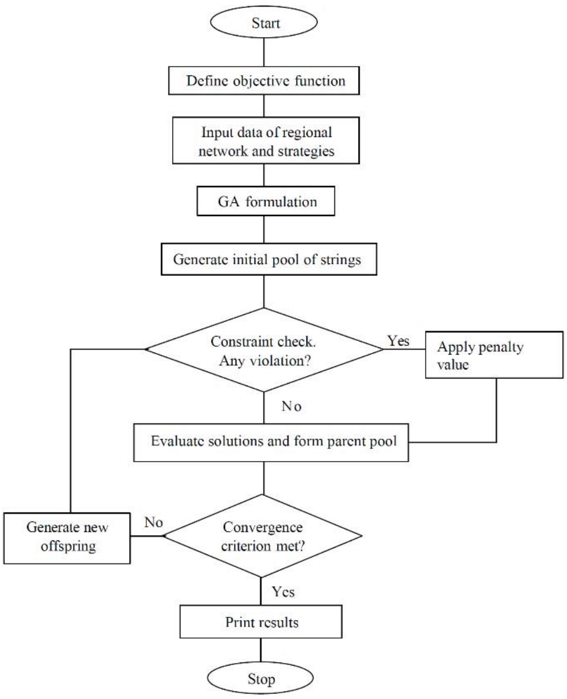

Figure 2. Flow chart for process of genetic algorithm optimization

In order to define the objective functions, there is need to collect suitable data. Table 3 in addition to the field survey information provided by the roads and bridges department in the region; data are shown in Table 2.

Accordingly, from precedence table can be reached to clarify the objective functions, and it defined by three objectives, which is the first one it to minimize the maintenance costs and the two other objectives are to maximize both the road rating and the service road life extended.

9. OBJECTIVE FUNCTIONS AND CONSTRAINTS

As the objective functions and constraints of the roadway, the GA formulation and optimization analysis are performed to evaluate the maintenance costs. When conducting the optimization process for the maintenance of road sections, we need to determine the most important goals to be reached, namely:

- Increase the road condition (road evaluation).
- Etending the service life of the road.
- Carry out maintenance work according to assigned costs and under budget limits.

9. 1. Objective Functions

This section presents the mathematical expressions of objective function for Kut-Baghdad roadway:

a. The objective function is to maximize the useful service life (USL) of the road through distressed road segments repaired, that is:

$$\text{Maximize } = \sum_{i=1}^{n} \sum_{j=1}^{m} X_{ij} * UI_{ij} \quad (2)$$

where, i is the chosen segment number ; j is type of maintenance strategy options; n is total number of pavement segment of the road; m is total number of pavement maintenance options; UIij is useful service life extended index of road segment; Xij is value between 0 and 1 represent the percent of segment of roadway under treatments.

The final formulation will be:

Maximizing = {$0.3*x_{11} + 0.4*x_{12} + 0.5*x_{13} + 1*x_{14} + 0.3*x_{21} + 0.4*x_{22} + 0.5*x_{23} + 1*x_{24} + 0.3*x_{31} + 0.4*x_{32} + 0.5*x_{33} + 1*x_{34} + 0.3*x_{41} + 0.4*x_{42} + 0.5*x_{43} + 1*x_{44}$}

b. The objective function is to minimize the total maintenance expenditure, as given below:

$$\text{Minimize } = \sum_{i=1}^{n} \sum_{j=1}^{m} C_{ij} * X_{ij} \quad (3)$$

where, Cij is the maintenance costs incurred in road segment i with maintenance option j (Table 2). The final formulation will be as follows:

Minimizing Cost = {$1.75*x_{11} + 6.5*x_{12} + 3.5*x_{13} + 8.5*x_{14} + 1.75*x_{21} + 6.5*x_{22} + 3.5*x_{23} + 8.5*x_{24} +$

$1.75*x_{31} + 6.5*x_{32} + 3.5*x_{33} + 8.5*x_{34} + 1.75*x_{41} + 6.5*x_{42} + 3.5*x_{43} + 8.5*x_{44}\}$

c. The objective function is to maximize the condition rating of the road through distressed road segments repaired, that is:

$$\text{Maximize } = \sum_{i=1}^{n} X_i * \frac{1}{d_i} \quad (4)$$

where di is the PCI rating for each road segment (Table 3). The final formulation will be:

Maximizing PCI Rating = $\{3.57 *x_{11} + 3.57 *x_{12} + 3.57 *x_{13} + 3.57 *x_{14} + 8.33*x_{21} + 8.33*x_{22} + 8.33*x_{23} + 8.33*x_{24} + 3.26*x_{31} + 3.26*x_{32} + 3.26*x_{33} + 3.26*x_{34} + 1.89*x_{41} + 1.89*x_{42} + 1.89*x_{43} + 1.89*x_{44}\}$

9. 2. Constraint of Objective Function The objective function is subject to the following constraints:

9. 2. 1. Maintenance Expenditure The total maintenance expenditure must not exceed the total budget allocated, as given by:

$$\sum_{i=1}^{n} \sum_{j=1}^{m} C_{ij} * X_{ij} \leq Bl \quad (5)$$

where, Bl the budget allocated to road. The final formulation will be:

$1.75*x_{11} + 6.5*x_{12} + 3.5*x_{13} + 8.5*x_{14} + 1.75*x_{21} + 6.5*x_{22} + 3.5*x_{23} + 8.5*x_{24} + 1.75*x_{31} + 6.5*x_{32} + 3.5*x_{33} + 8.5*x_{34} + 1.75*x_{41} + 6.5*x_{42} + 3.5*x_{43} + 8.5*x_{44} \leq 15$

9. 2. 2. Non Negative Value The value of variable X_{ij} should not to be negative value (between 0 and 1).

$$0 \leq X_{ij} \leq 1 \quad (6)$$

9. 2. 3. Select one Strategy The objective functions optimization should be selected one option of maintenance strategy as follow:

$$\sum_{j=1}^{m} X_j \leq 1 \quad (7)$$

10. RESULTS AND INTERPRETATION OF THE FINDINGS

The results of applying the genetic algorithms multi-objective explained in the next figure, the result are presented in Figures 3 and 4; which obviously shown that the Pareto interface can be obtained using the proposed approach and that a uniform allocation can be achieved by changing the different objective weights. Each point in the graph required independent operation with a defining number population and more than 100 iterations.

Figures 3 and 4 show the relation between the objective functions, where the Figure 3 clearly presented evidence to how the increase in the PCI will lead to extend the roadway useful life.

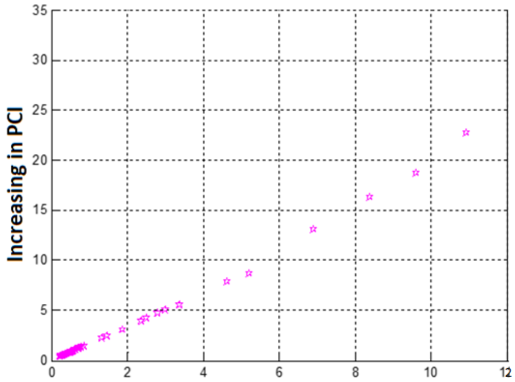

Figure 3. Relation between increasing in the PCI and useful life extend

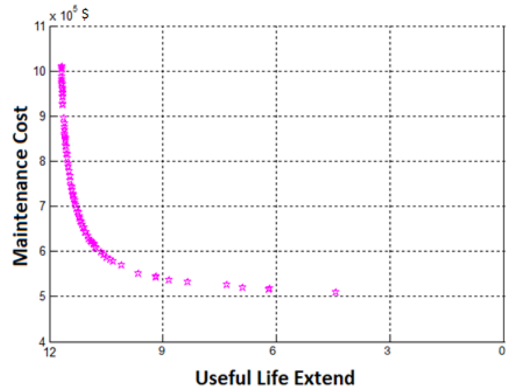

Figure 4. Effect of maintenance cost on extend of roadway useful life

While Figure 4 shows the effect of availability budget for funding the maintenance cost on extend of roadway useful life.

The followed Figure 5 displays the percent of each maintenance strategy option that will be applied to reach optimum benefit from allocated budget that lead to the best PCI and more fitness from the side of useful life extend. The main purpose of performing maintenance work is to either maintain the service provided, prevent the pavement from collapsing, or extend the service life of the road.

After applying the genetic algorithm optimization and taking into consideration the limited budget as a constraint, it was found that its used as a decision tool was suitable to reach an optimal distribution of maintenance work on all road sections according to the alternatives provided for the system.

Thus, the proportions of each of these alternatives are distributed in Table 3 for each road sections.

Depending on the values shown in Table 1, it is noted that the maintenance strategy described in Table 3 is applied. It will contribute to extend the service life of the road by 1.2 year. At the same time, it will increase PCI by 3.8 % for overall road rating.

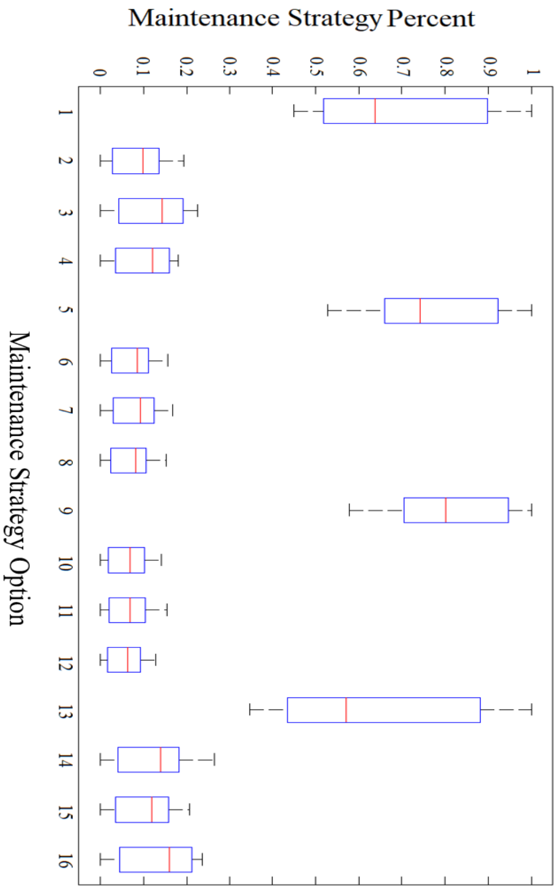

Figure 5. Percent for each maintenance strategy

TABLE 3. Maintenance strategy alternative for each road sections area percentage

Maintenance Strategy	Sec. 1	Sec. 2	Sec. 3	Sec. 4
Crack Treatment	0.38	0.26	0.24	0.42
Patching	0.12	0.09	0.07	0.19
Slurry Seal	0.17	0.12	0.09	0.14
Thin Overlay	0.14	0.09	0.07	0.24

Tables 4 and 5 show increasing in PCI percentage also the extended service life for each section according to the maintenance procedure taken.

TABLE 4. Maintenance strategy alternative contribution in extended service life for each road sections

Maintenance Strategy	Sec. 1	Sec. 2	Sec. 3	Sec. 4
Crack Treatment	1.14	0.78	0.72	1.26
Patching	0.48	0.36	0.28	0.76
Slurry Seal	0.85	0.60	0.45	0.70
Thin Overlay	1.40	0.90	0.70	2.40

TABLE 5. Maintenance strategy alternative contribution in pci increasing for each road sections

Maintenance Strategy	Sec. 1	Sec. 2	Sec. 3	Sec. 4
Crack Treatment (%)	1.9	1.3	1.2	2.1
Patching (%)	0.6	0.5	0.4	1.0
Slurry Seal (%)	5.1	3.6	2.7	4.2
Thin Overlay (%)	4.9	3.2	2.5	8.4

11. CONCLUSIONS

This paper presents optimization process with a multi-objective programming, used maximizing level of user comfortable through increasing PCI rating of roadway as measured. It examines the prioritizing optimization of the road segments that is needed for maintenance using the genetic algorithm based on useful service life and pavement condition as an objective function. The constraints faced is maintenance cost must not be exceeding the limited yearly financial (budget limit) as well as the non-negatively constraint. This research presents approach to find optimum maintenance alternative according ability limiting of funds allocated by Governorate to each project. The research reaches to the following recommendations:

1. The rapid deterioration in Iraqi roads in general has been observed due to negligence in regular and planned maintenance of the roads. So there is need to manage road maintenance in a systematic and continuous manner.
2. The adoption of this model by the bodies responsible for the maintenance of roads will be of great benefit by providing them with a clear vision of the behaviour of pavement and the extent of the deterioration. Thus, provide a basis for prioritizing the provision of funds to maintain road sections subject to failure.
3. Moreover, other studies can be developed using maintenance strategy with other option, overlooking from standard strategy that has been adopted in this work.
4. The adoption of optimization in decision-making, greatly helps decision makers in determining maintenance priorities and an optimal distribution of the budget, although it is limited, so, the project can be reached to the best rate of improvement in performance.
5. Available budget contributes to extend the service life of the road by 1.2 year. At the same time, it will increase PCI by 3.8 % for overall road rating, as a result of applying genetic algorithms optimization for each section according to the maintenance procedure taken.
6. It is possible to conduct additional studies comparing the different optimization methods and showing the difference between their results on increase in road rating and the value of service life extended.

12. ACKNOWLEDGEMENTS

Baghdad University, supported this project. Authors are thankful to roads and bridges directorate of Wasit, who has provided the information related with budget limit allocated to maintenance work.

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Persian Abstract

چکیده

منابع و بودجه محدود مهمترین مشکل در بخش مدیریت راه است ، بنابراین تخصیص نیازها و اولویت های نگهداری و توانبخشی در زمان مناسب و منطقی مهمترین عوامل است. برای جلوگیری از نتیجه بدتر شدن در اثر تکرار وزن وسیله نقلیه و همچنین سایر عوامل مانند عوامل محیطی، جاده ها درخواست کار مداوم دارند. این که آیا با بودجه تخصیصی که برای کارهای مربوط به تعمیر و نگهداری جاده ها اختصاص داده شده است، لازم است که از بودجه به دست آمده استفاده بهینه استفاده شود. برای اجرای این روش، یک رویکرد منظم برای فرایند برنامه ریزی برای دستیابی بهینه از مزایای بخش جاده و به حداقل رساندن بودجه و هزینه های لازم برای تکرار روسازی در حالت اول. این فرآیند به عنوان سیستم مدیریت تعمیر و نگهداری پیاده رو تعریف شده است. بنابراین، رویکرد، مؤثرترین کارآیی بودجه، کار، تجهیزات و سایر منابع را به آژانس اختصاص می دهد. در این مقاله روند استفاده از برنامه نگهداری با توجه به بهینه سازی الگوریتم ژنتیک نشان داده شده است. هدف از آن دستیابی به درصد جایگزین استراتژی تعمیر و نگهداری کم برای دستیابی به بهترین مقادیر برای عمر سرویس تمدید شده و همچنین افزایش شاخص وضعیت روسازی (PCI) به همراه بودجه مشخصی است که برای بازگرداندن کل پیاده رو به حالت قبلی خود کافی نیست. پس از استفاده از این برنامه ، مشخص شد که طول عمر سرویس اضافی را به جاده (۱.۲ سال) می دهد و در عین حال با در نظر گرفتن منابع محدود اختصاص یافته برای نگهداری ، مقدار(3.8 PCI ٪ را نیز افزایش می دهد.