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An Integrated Optimization Model for Life Cycle Pavement Maintenance Budgeting Problems

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ABSTRACT Driven by the demand to preserve the existing road pavement condition, the issue of selecting maintenance action at the appropriate time under budget limitation has attracted great attention from highway agencies. This study focuses on the strategy of how to manage pavement maintenance budget effectively on road network level based on life cycle cost analysis. The framework of resource-constrained project scheduling problem (RCPSP) is implemented to establish a maintenance action decision-making mechanism for allocating pavement maintenance budgets on the planning and controlling phases. In the RCPSP environment, a two-stage optimization model based on constraint programming techniques is developed to meet two different management goals such as 1. annual budget evaluation from planning points of view, and 2. actual budget adjustment from the controlling point of view, by considering the factor of road usability. Model-I, the life cycle lifespan evaluation model solves the problem of annual budget evaluation to satisfy the maintenance requirements of all road sections. The optimal maintenance plan then can be made to maintain road performance and evaluate annual budget requirement for future years to maximize total maintenance benefits, in terms of the overall maximum pavement lifespan. Based on the suggested results of budget evaluation from Model-I, Model-II, the actual budget adjustment model deals with the actual budget allocation problem of how to keep up the original maintenance budget plan when the actual budget is always awarded insufficiently each year. Finally, the proposed two-stage integrated models provide an optimal maintenance strategy to respond to actual maintenance status and pavement deterioration as feedbacks to the actual budget adjustment model, and recursively make pavement maintenance strategy closer to actual conditions by budget adjustment yearly.

INDEX TERMS Pavement maintenance, life cycle cost, budget allocation, resource-constrained project scheduling, constraint programming.

NOMENCLATURE

A. Indices:

h	Road number indices.
i	Road type number indices.
j	Maintenance plan cycle number.
k	Maintenance plan selection.
l	Year number in road life cycle.
c	Current plan selection.
n	Considered time periods selection.

B. Parameters:

r	Total number of considered roads.
t	Total number of considered road types.
p	Total number of maintenance plans.
q	Total number of considered time periods.
y	Numbers of year in a life cycle.
z	Numbers of maintenance plan cycles in a life cycle.
ft_i	Road type.
w_h	Weight of road priority.
$fcb_{h,i,k}$	Maintenance plan stage B cost for road.
$fcm_{h,i,k}$	Maintenance plan stage M cost for road.
$fcu_{h,i,k}$	Maintenance plan stage M cost for road.
$dfb_{h,i,k}$	Maintenance duration stage B for road.
$dfm_{h,i,k}$	Maintenance duration stage M for road.
$dfu_{h,i,k}$	Maintenance duration stage U for road.
$fbm_{h,i,k}$	Existing road maintenance in the current plan.
$rab_{h,i,l}$	Budget limit in year.

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$rfp_{h,i,l}$ User cost after then end of service life in year.

$ruf_{h,i,k,l}$ Available resource in a year.

C. Variables:

$PBS_{h,i,k}$ Start time of selected maintenance plan on stage B in current time.

$PMS_{h,i,k}$ Start time of selected maintenance plan on stage M in Current Time.

$PUS_{h,i,k}$ Start time of selected maintenance plan on stage U in current time.

$UPD_{h,i,k}$ Current maintenance duration on stage U.

$UPC_{h,i,k}$ Current maintenance cost on stage U.

$PBE_{h,i,k}$ Finish time of selected maintenance plan on stage B in current time.

$PME_{h,i,k}$ Finish time of selected maintenance plan on stage M in current time.

$PUE_{h,i,k}$ Finish time of selected maintenance plan on stage U in current time.

$BS_{h,i,k,n}$ Start time of selected maintenance plan on stage B in considered time periods.

$MS_{h,i,k,n}$ Start time of selected maintenance plan on stage M in considered time periods.

$US_{h,i,k,n}$ Start time of selected maintenance plan on stage U in considered time periods.

$BE_{h,i,k,n}$ Finish time of selected maintenance plan on stage B in considered time periods.

$ME_{h,i,k,n}$ Finish time of selected maintenance plan on stage M in considered time periods.

$UE_{h,i,k,n}$ Finish time of selected maintenance plan on stage U in considered time periods.

$EX_{h,i,k,n}$ Option of maintenance plan k for a road h in considered time periods.

$PCD_{h,i,n}$ Binary variable representing whether duration option and cost option at the current time for a road should be select, $PCD_{h,i,n} \in [0,1]$.

$PRB_{h,i,k}$ Resource use when a road on maintenance of stage B in current time.

$PRM_{h,i,k}$ Resource use when a road on maintenance of stage M in current time.

$PRU_{h,i,k}$ Resource use when a road on maintenance of stage U in current time.

$BD_{h,i,k,n}$ Maintenance plan duration stage B for a road in considered time periods.

$MD_{h,i,k,n}$ Maintenance plan duration stage M for a road in considered time periods.

$UD_{h,i,k,n}$ Maintenance plan duration stage U for a road in considered time periods.

$BC_{h,i,n}$ Maintenance cost stage B in considered time periods.

$MC_{h,i,n}$ Maintenance cost stage M in considered time Periods.

$UC_{h,i,n}$ Maintenance cost stage U in considered time periods.

$UCD_{h,i,n}$ Binary variable representing whether duration option and cost option for a road should be select, $UCD_{h,i,n} \in [0,1]$.

$RFB_{h,i,k}$ Resource use when a road under maintenance on stage B in considered time periods.

$RFM_{h,i,k}$ Resource use when a road under maintenance on stage M in considered time periods.

$RFU_{h,i,k}$ Resource use when a road under maintenance on stage U in considered time periods.

$BDY_{h,i,k}$ Maintenance plan duration stage B for a road in considered time periods of Model II.

$MDY_{h,i,k}$ Maintenance plan duration stage M for a road in considered time periods of Model II.

$UDY_{h,i,k}$ Maintenance plan duration stage U for a road in considered time periods of Model II.

$BCY_{h,i,k}$ Maintenance plan cost stage B for a road in considered time periods of model ii.

$MCY_{h,i,k}$ Maintenance plan cost stage M for a road in considered time periods of Model II.

$UCY_{h,i,k}$ Maintenance plan cost stage U for a road in considered time periods of Model II.

$BSY_{h,i,k}$ Start time maintenance plan stage B in considered time periods of Model II.

$MSY_{h,i,k}$ Start time maintenance plan stage M in considered time periods of Model II.

$USY_{h,i,k}$ start time maintenance plan stage U in considered time periods of Model II.

$YF_{h,i,k,n}$ Binary variable representing whether a road is under maintenance in considered time periods of Model II, $YF_{h,i,k,n} \in [0,1]$.

$BRY_{h,i,k}$ Resource use when a road under maintenance on stage B of Model II.

$MRY_{h,i,k}$ Resource use when a road under maintenance on stage M of Model II.

$URY_{h,i,k}$ Resource use when a road under maintenance on stage U of Model II.

C. Sets:

SU Set of roads under maintenance.

SM Set of maintenance plans.

SR Set of resource type.

SD Set of duration maintenance activity.

SC Set of cost maintenance activity.
SI Set of road types under maintenance.
SY Set of year selection.

I. INTRODUCTION

In most developed countries, the construction of major road networks has been is almost completed. Those finished roads require regular pavement maintenance to preserve the road serviceability performance, and pavement maintenance requires huge maintenance funds [1]. The issue of road maintenance project budgeting is mostly experience-oriented. The maintenance program of road facilities under local road authorities is typically made by their experience to plan maintenance budgets and submit them to higher authorities for approval based on the road current conditions, where the way of budgeting process is bottom-up. It can be explained that the road authorities at each level, as budget planners, propose their own annual needs according to the current situation and submit them to their superiors, who then examine and approve them as budget reviewers. The budget planners propose reasonable budget plan based on the overall current situation of their facilities. While the budget reviewers from a higher perspective in the face of budget constraints need to consider the plans of all lower-level agencies to make proper budget allocation decisions. With the different perspectives of the upper and lower levels, the following year's budget may not always be approved in accordance with the life cycle proposals of all road sections. The lower-level agencies as the budget recipient have to bear the burden of underfunding. Obviously, such challenge relies on how the budget recipient re-adjusts the approved but insufficient budget to maximize overall maintenance effectiveness.

Therefore, in this study, we propose an integrated optimization model for life cycle pavement maintenance budgeting problems, based on the concept of resource-constrained project scheduling problem (RCPSP) to address the maintenance budget planning of road networks. The RCPSP is the resource allocation oriented framework, which focuses on the implementation of all resource limitations held by projects [2]. For example, in construction industry, the number of available construction resources such as labors and materials is set as an upper limit for each resource, such as steel construction welding work and their supporting professional and technical welding personnel. In other words, in addition to the relationship between construction operations (activity precedence), we must also consider the scheduling of resources, so that the limited resources will not be left idle as much as possible to achieve the maximum project benefit. From this point of view, the road sections to be maintained in this study are regarded as resources in RCPSP setup. When the resources are not idle, it implies that the road sections are in usable condition and function normally. Such concept is consistent with the goal of solving the RCPSP problem. Therefore, this study adopts RCPSP framework to deal with the problem of pavement maintenance budgeting problems. The advantage of employing the RCPSP concept in the proposed model is to minimize the unusable situation of the road sections, if insufficient maintenance action is performed under an unsatisfactory budget scenario.

Generally, in real situations, pavement maintenance accounts for the largest portion of road maintenance projects. According to their natures, road pavement types can be divided into flexible pavement (Asphalt Concrete Pavement) and rigid pavement. Among two of them, the use of flexible pavement is more widespread [3]. Therefore, this study focuses on the maintenance of flexible pavement as the main research objective. A two-satge integrated optimization model is developed for both of budget planning and controlling phases. Model-I uses the concept of life cycle for road maintenance budget planning at the road network level to provide a reference for local units to submit maintenance budget proposals to higher authorities. While model-II focuses on the situation where budgets may reduce after the actual budget is issued in the current year at budget controlling phase, and the maintenance plan of the road network is rearranged refer to the issued actual budget.

The subsequent chapters of this paper are summarized as follows. Chapter 2 describes the existing research in road maintenance planning and some previous studies of RCPSP. Chapter 3 is a methodological description of the application of the RCPSP concept to life cycle pavement maintenance budgeting problems. Chapter 4 illustrates the proposed two-stage optimization model and validates the model with real cases in Chapter 5, and finally concludes in Chapter 6.

II. LITERATURE REVIEW

The effectiveness of pavement maintenance problems has been a major concern for many practitioners and researchers in the past decades. Hence, many studies were and being applied by practitioners or academics to increase the efficiency of pavement maintenance management in decision-making and coordinating the maintenance activities that bring a direct effect on road network systems. Many methods have been used to perform the studies of pavement maintenance management problems, such as optimization, life-cycle cost analysis (LCCA), Analytical Hierarchal Process (AHP), statistical analysis, and Data Mining (DM), as well as combinations of those methods. Most of those studies utilized an optimization approach to develop effective pavement maintenance strategies considering several issues, such as maintenance budget, operational cost, weather effect, environmental impact, energy consumption, user cost, and road safety.

One optimization model applied to develop pavement maintenance strategy was linear programming (LP) technique. This technique was performed by Kuhn and Madanat [4] to find the optimum cost-effectiveness between ignored uncertainty conditions and considered uncertainty conditions on pavement deterioration by utilizing the Markov decision problem (MDP). The developed LP optimization model was demonstrated could control worst-case cost expenditures for pavement scheduling maintenance, repair, and rehabilitation (MR&R). Furthermore, the LP technique for pavement maintenance planning was also performed by [5] to develop a multi-objective optimization model (MOO) based on four performance indicators were pavement condition index (PCI), present serviceability index (PSI), international roughness index (IRI), and average accident number. Consider those performance indicators the MOO model attempts to minimize the maintenance cost while satisfying the standard of those indicators.

Besides the LP technique, dynamic programming (DP) was considered by other studies to develop the pavement maintenance optimization model. Durango-Cohen and Madanat [6] developed a pavement maintenance optimization model under uncertainty performance of Markov decision process (MDP) with utilizing the quasi-Bayes under DP technique framework to minimize cost expenditure and obtain timely maintenance action in a finite time horizon. Kuhn [7] further proposed an optimization model of pavement maintenance strategy that focused on the pavement physical condition and the pavement composite condition index to minimize social costs with respect to the available resources of the public agencies. Approximate dynamic programming (ADP) was applied in the model to select a proper maintenance action under a limited resource that ensures pavement serviceability at the road network level. Medury and Madanat [8] compared ADP and LP techniques based on the MDP model for developing a decision-making method in pavement MR&R strategy that integrated the restriction of financial resources to minimize maintenance costs from a planning process up to the operational-level implementation in road network-level. Medury and Madanat [9] extend their previous study based on the MDP by demonstrated a simultaneous network-level optimization in pavement management systems to satisfy the gap between the top-down and bottom-up MDP approaches. The top-down approach was formulated using the LP method to minimizes the expected system-level user-plus-agency cost in a certain planning duration. Subsequently, a DP method was utilized for the bottom-up approach to minimizes the expected cost-to-go from the current year to the end of planning time. Lee and Madanat [10] proposed an optimization model for pavement maintenance repair and rehabilitation (MR&R) planning employing DP technique to minimizes total discounted lifetime costs over an infinite time horizon. Markovian deterioration model and history-dependent deterioration model were analyzed to optimizes reconstruction intervals jointly with maintenance and resurfacing policies.

The other dynamic programming (DP) models on pavement maintenance strategy that consider energy consumption and environmental impact were performed by Zhang *et al.* [11], Yu *et al.* [1], and Huang *et al.* [12]. Zhang *et al.* [11] refer to life-cycle cost analysis (LCCA) and pavement deterioration model developed an optimization model to minimize total life-cycle energy consumption, greenhouse gas (GHG) emissions, and maintenance costs. Furthermore, Yu *et al.* [1] with a similar optimization model accommodated environmental damage cost (EDC) of Portland cement concrete (PCC) pavement and hot mix asphalt (HMA) pavement. Lastly, Huang *et al.* [12] minimized the overall cost of pavement service life by considering three dimensions of multi-objective problems includes maintenance performance, economic impacts, and environmental impacts.

The other pavement maintenance optimization studies were conducted utilizing integer programming (IP), mixed-integer programming (MIP), and mixed-integer non-linear programming (MINLP). The studies utilizing integer programming (IP) optimization approaches were performed by Wang *et al.* [13] that presented a concept of clustering pavement segments with the same maintenance treatment into cost-effective pavement maintenance and rehabilitation (M&R) projects for minimizing the total pavement M&R cost at the road network level. Guo *et al.* [14] combined the IP approach and Monte carlo simulation to generate a range of future scenarios at the road segment level to minimize the total cost at the network level and optimize the maintenance budget allocation. Shi *et al.* [15] conducted a similar IP approach for minimizing total maintenance cost by considering pavement deterioration using IRI as a pavement indicator and Markov chain model as a deterioration model. A mixed-integer programming (MIP) approach was applied by Chu and Huang [16] to optimize road network pavement maintenance based on four strategies include optimization-based, worst-first, best-first, and threshold base with considering traffic, different budget levels, initial pavement condition, and heterogeneous effects of maintenance treatments. A mixed-integer nonlinear programming (MINLP) technique was employed by Ouyang and Madanat [17] to minimize the pavement life cycle cost that considers user cost and agency cost under pavement deterministic deterioration model and limited budget. Ouyang and Madanat [18] extend their MINLP model by accounted pavement resurfacing activities in continuous time to keep the serviceability pavement performance on multiple highway facilities. Another MINLP model was performed by Lee and Madanat [19] in minimizing the net present value of discounted lifecycle costs based on the non-Markovian deterioration model with considering pavement construction cost, maintenance cost, and user cost.

Furthermore, genetic algorithm (GA) and particle swarm optimization (PSO) techniques were also frequent optimization techniques in developing an optimization model in pavement maintenance strategy. Such as, Fwa *et al.* [20] presented a multi-objective optimization (MOO) under budget constraint by utilizing a genetic algorithm (GA) to obtain the optimum solution from three multi-objective functions includes cost, pavement performance, and working duration. Lu and Tolliver [21] proposed a MOO model utilizing a GA approach to find the optimum solution of two objective functions were consist of total agency cost and pavement network average roughness that considers weather effect. Denysiuk *et al.* [22] also conducted the MOO GA approach in two-stage optimization, the first stage was solving two objective functions of minimizing pavement degradation and minimizing maintenance cost for individual road sections.

Objective functions in the second stage were minimizing the variation of maintenance costs and the total cost of maintenance for all road sections in the road network. A similar MOO in a nondominated sorting genetic algorithm (NSGA-II) was performed by Khiavi and Mohammadi [23] to solve three objective functions, there are minimizing the maintenance cost, minimizing user cost, and maximizing the residual value of pavement at the end of service life on the large scale of road network.

Other studies that employed GA with taking into account the environmental impact factor were performed by Yu *et al.* [24] and Cao *et al.* [25]. Yu *et al.* [24] developed a GA model that integrated Life Cycle Assessment (LCA) and Life Cycle Cost Analysis (LCCA) by considering material production, transportation, onsite construction, usage, and energy consumption for LCA as well as evaluates agency cost, user cost, and salvage value for LCCA to maximize pavement performance efficacy while also minimizing environmental impact. Cao *et al.* [25] proposed a Multi-Objective Optimization of pavement maintenance activities using the NSGA-II algorithm by considers maximizing the average noise reduction segment per year, minimizing maintenance cost, and minimizing GHG emissions.

The multi-objective particle swarm optimization (MOPSO) technique was employed by Chou and Le [26] to maximize pavement systems reliability throughout the pavement service life and Ahmed *et al.* [27] to minimize maintenance cost and minimize the sum of all residual pavement condition index (PCI) values.

The other mathematical programming such as the greedy algorithms approach was performed by Sathaye and Madanat [28] to minimize user cost and agency cost in pavement resurfacing strategy under restriction budget and deterministic linear deterioration model on multiple highway facilities. Gu *et al.* [29] formulated a nonlinear mathematical model that incorporates the effects of maintenance activities and pavement deterioration in the pavement resurfacing problem to minimize the total pavement life cycle cost, taking into account user costs, resurfacing costs, and maintenance costs. Chu and Chen [30] proposed a nonlinear mixed-integer bi-level optimization with objective function of the upper-level was to minimize the system-wide traffic weighted of pavement performance according to the International Roughness Index (IRI) and the objective function for the lower-level was to minimize the travel time of road users. Zhang *et al.* [31] were promotes a Lagrange multiplier approach combine with derivative-free quasi-Newton algorithms to minimize the total expenditure cost to both the highway agency and the highway users in a system of heterogenous pavement segments under budget limitation. A constraint programming (CP) approach was performed by Hankach *et al.* [32] to minimize total maintenance cost subject to budget constrain and statistical deterioration model on the road network level. A different approach was performed by Torres-Machi *et al.* [33] which utilizes a hybrid Greedy Randomized Adaptive Search Procedure (GRSAP) to minimize environmental impact while maximizing pavement long-term effectiveness (LTE) on pavement maintenance strategy under a limited budget.

Besides the optimization approach, several studies performed another different numerical analysis approach. Vassallo and Izquierdo [34] proposed a pavement maintenance management model that provides economic evaluation, the model was integrated with management and financing sub-model, maintenance expenses and investment sub-model, transport cost sub-model, traffic sub-model, and pavement deterioration sub-model. Labi and Sinha [35] developed pavement life-cycle preventive maintenance (PM) on the statistical model's framework to obtain maintenance cost estimation and effort effectiveness within prolonging pavement service life. Yoon *et al.* [36] presented a modified minimum moment method with the dummy period to minimizes the variance of pavement maintenance cost among annual budgetary requirements over a multiyear period of pavement service life. Heravi and Esmaaeli [37] proposed a multi-criteria decision-making method by applying LCCA that utilizes fuzzy set theory. Includes in these criteria were extra user costs attributable to unsatisfied pavement conditions and pavement serviceability performance. Zheng *et al.* [38] proposed a methodology of pavement life-cycle sustainability assessment (LCSA) utilizing Analytical Hierarchical Process (AHP)-VIKOR for selecting an optimum alternative among three different types of hot mix asphalt includes thin hot mix asphalt (THMACO), hot mix asphalt with warm mix (HMAW), and hot mix asphalt with reclaimed asphalt pavement (HMAR) by considering the economic, environmental, and social dimensions. Torres-Machi *et al.* [39] proposed an optimization design of sustainable maintenance strategies based on pavement preservation and rehabilitation that evaluated using a cost-effectiveness evaluation and environmental evaluation. Han *et al.* [40] presented a pavement maintenance strategy employing the fourth-order method of moments that considers the failure probability and reliability of pavement performance to minimize the pavement cost per unit time. Another different approach utilizing Artificial Neural Network (ANN) with a pattern-recognition algorithm was performed by Hafez *et al.* [41] to develop a decision-making model in specifying the optimum pavement maintenance and rehabilitation alternatives at a road network level based on drivability life (DL) of pavement condition.

The other studies emphasized employing Life Cycle Cost Analysis (LCCA) in evaluating various costs associated with the types of pavement maintenance and pavement deterioration characteristics to obtain the most fitness's pavement maintenance strategy. For instance, Han and Do [42] based on the Korean National Highways data and the Markov chain pavement deterioration models analyzed pavement maintenance work delay to find the optimal maintenance intervention interval for 40-year life expectancies. The LCCA model consisted of the maintenance cost, inspection cost, vehicle operation cost (VOC), accident cost, vehicle emission cost, economic analysis, and vehicle speed estimation.

Wang and Wang [43] conducted a study LCCA of pavement in the United States of America (USA) and Canada based on the International Roughness Index (IRI) concept that focused on vehicle operation cost (VOC), agency cost, and annual daily truck traffic (AADTT) to optimize maintenance timing in 20 years. Abaza [44] performed a similar LCCA study on the urban arterial road in West Bank-Palestine used a Markov deterioration model considering initial construction cost, routine maintenance cost, major rehabilitation cost, and the added user cost due to work zones to determine the pavement life cycle performance and proper maintenance for the pavement service life in the next 20-year. Onyango *et al.* [45] examined LCCA of pavement primary arterials road in the city of Chattanooga-USA according to seven pavement deterioration models based on pavement condition index (PCI) to define the optimum pavement maintenance and repair (M&R) budget in the next 10 years. Braham [46] based on Arkansas-USA highways data utilized LCCA to examined two pavement maintenance types includes a seal for 6 years and a 2-in overlay for 11 years that consider agency cost and user cost to determine proper maintenance type according to full-depth reclamation (FDR) pavement rehabilitation concept.

Instead of analyzing the cost variable of the pavement maintenance strategy, another study emphasizes analysis of the environmental performance of the pavement. Such as, Santos *et al.* [47] focused evaluated the environmental impact of pavement maintenance by applying the life cycle assessment (LCA) concept in Virginia-USA that considers material production, construction and M&R, transportation materials, work zone traffic management, usage pavement, and pavement end-of-life (EOL). The pavement condition was evaluated for 50 years based on the IRI method and modified structural index (MSI) deterioration model.

Moreover, rather than adopting an advanced optimization model or other numerical methods, another study strives to compare several different methods. For example, France-Mensah and O'Brien [48] examined three different methods developed an optimum budget allocation model for pavement maintenance and rehabilitation in a certain planning horizon. The methods utilized in this study were ranking-based, mathematical optimization integer linear programming (ILP), and data mining (DM) approach. The models were assessed based on performance measures of equity, effectiveness, and strategic goal. From three different methods, the ILP was revealed as the most effective method compared to others methods.

In this study, the pavement maintenance strategy involves the consideration of the maintenance activity and pavement life cycle. Through literature review, there's no prior studies ever attempting to combine the maintenance activity and pavement life-cycle concept, from the perspective of maintenance budgeting problem. By viewing the maintenance stage as project activity in the pavement maintenance strategy, we can then utilize the RCPSP framework to develop a brand-new pavement maintenance strategy. RCPSP is a well-known scheduling method to overcome a complex set of activities subject to precedence constraints relationship under the resource limitation condition for minimizes the total makespan [49]. Hanzalek and Sucha [50] formulated a lacquer production scheduling problem as an RCPSP concept using a mixed-integer linear programming (MILP) technique that considers take-give resources from the beginning to the completion of the production process. Chakraborty *et al.* [51] proposed an extension of RCPSP named stochastic resource-constrained project scheduling problem (SRCPSP) which minimizes the makespan of a project considers the uncertain characteristic of reality into stochastic activity durations by utilizing a constrained logic programming (CLP) technique. Chakraborty *et al.* [52] continued using the RCPSP concept for solving resource disruptions problems on production process scheduling by applying a continuous-time (CT) based reactive scheduling approach in the MILP framework. Oztemel and Selam [53] developed a Bees Algorithm to cope with a single resource on multi-mode of RCPSP to minimize the mold project duration with different sizes ranging from 10-jobs to 80-jobs projects. Liu *et al.* [54] proposed RCPSP in GA framework to solve standard problems taken from Project Scheduling Library (PSPLIB) with forward-backward improvement (FBI) procedure. The results then compare to 19 other metaheuristics studies, includes ant colony optimization, particle swarm optimization, scatter search, shuffled frog leaping algorithm, artificial immune algorithm, and bee algorithm. Kong and Dou [2] proposed Constraint Programming model to overcomes RCPSP under multiple time constraints including activity duration constraints, temporal constraints, and resource calendaring constraints.

The optimization approach was proven by prior studies, as the most prominent technique to solve pavement maintenance strategy problems. However, only a few previous studies adopted Constraint Programming (CP) technique into the optimization model for pavement maintenance strategy (Hankach *et al.* in reference 32), and none of those studies utilized the RCPSP concept. Therefore, this study endeavors to apply an optimization approach in developing the maintenance budgeting planning for pavement maintenance strategy by applying constraint programming (CP) technique in the RCPSP framework. Employment of the RCPSP concept based on life cycle cost analysis in this study presents a novel approach to develop an activity-based project network for a long-term practical pavement maintenance strategy.

III. METHODOLOGY

The following subsections describe how this study defines road availability, the algorithm used to solve the problem, and how the RCPSP concept is applied to life cycle planning of road maintenance.

A. PAVEMENT CONDITION INDEX AND USABILITY DEFINITION

There are several indicators used to assess the performance of pavement, and many countries develop their own pavement assessment models according to the current conditions of pavement environment. According to the pavement condition index (PCI) method (ASTM D6433) for measuring the pavement condition adopted by Onyango *et al.* [45], preventive maintenance should be performed when the Pavement Condition Index (PCI) is between 70 and 100, and routine maintenance should be performed when the index is between 40 and 70. The so-called preventive maintenance is maintenance performed when the road pavement damage is still in the process towards critical pavement distress conditions, such as cracking, deformation, or potholes. The preventive maintenance will prevent severe pavement distress and it is recommended to carry out immediately after the preliminary defects appear. Routine maintenance commonly is performed when pavement already shows significant physical changes, such as cracking, material separation, deformation, surface peeling, surface abrasion, and other minor damage phenomenas. If such pavement conditions are not properly maintained in time then the external environment and vehicle traffic will affect the road. In a longer period, those defects will accelerate the reduction of road serviciablity.

The PCI represents the road section condition based on the severity of pavement distress assessment. The severity classification of pavement distress has a variety in thickness and extensions that determine the PCI value [55]. The PCI score of the road section is taken between two intersections as the starting point and the end point. This score is determined from the observation of pavement distress that occurs in each road section [56]. For example, when the road section doesn't have any defect, then the score is 100. When the defects are barely perceptible, then the score is close to 100. Referring to Pinatt *et al.* [56] and Onyango *et al.* [45], the PCI rating scale adopted in this study to define the pavement usability is from 70 to 100, representing satisfactory condition to good condition. Subsequently, PCI score from 40 to 70 represent poor condition to fair condition, and from 0 to 40, failed condition to very poor condition.

According to the above definitions, when the PCI value of the pavement is between 70 and 100, it implies that the road is usable in satisfactory to good condition. When the PCI value drops to the range between 40 and 70, the road remains usable in poor to fair condition, then needs to be maintained in order to upgrade the condition to a normal or acceptable condition. Once the PCI value drops to below 40, the pavement is an unusable condition with the current status in failed to very poor condition. According to the principle explained above, the degree of usability is defined as shown in Table 1.

TABLE 1. PCI level qualification.

PCI	Description
70-100	Satisfactory - Good
40-70	Poor - Fair
0-40	Failed – Very Poor

Therefore, the length of time it takes for the PCI to drop from 100 to 40 is the serviceable life of the road; and due to the lack of budget, the road cannot be maintained and the PCI may be lower than 40.

B. PAVEMENT MAINTENANCE PROBLEMS WITH RCPSP REPRESENTATION

With the concept of limited resource scheduling, by treating road facilities as resources, the solution process is to keep the resources from being idle as much as possible, meaning that the road facilities are kept in a usable state as much as possible, which is the same as the expectation of the road management unit. The maintenance project is the same as the operation (Activity) in the project scheduling. Thus, the problem of road maintenance budget allocation can be realized by the solution of RCPSP.

To express the road operation process completely in the model, this study divided the road maintenance process into three stages, i.e., build with code b, maintenance with code m, and useless with code u, and combined with the definition of PCI and this study road serviceable or not, a maintenance process as shown in Figure 1. The total duration of b and m is the serviceable years, and the duration of u is the allowable in-service years.

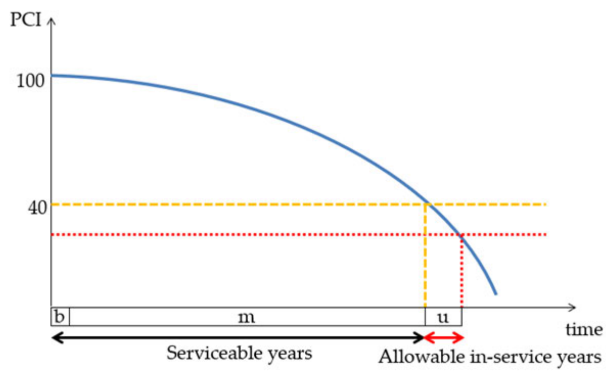

FIGURE 1. schematic diagram of pavement maintenance stages with PCI value deterioration.

The RCPSP concept of B, M, and U represents three operations (activities), meaning that this study considers B, M, and U as three different activities with a precedence relationship between the predecessor and the successor to each other, and each activity contains cost and duration.

B activities refer to the re-paving or renovation of existing road pavement, which can be divided into two major categories, fresh asphalt concrete, and recycled asphalt concrete, depending on the material. The construction method is based on the highway maintenance manual [57] for the reference of flexible pavement large maintenance method. Therefore, the cost and duration of stage b of RCPSP are shown in Table 2, which represent the actual construction cost and construction duration respectively.

M activities refer to the road service and maintenance period (duration). The cost and duration of stage m of the

TABLE 2. B-stage related parameters.

Parameters of Stage-B	Description
Cost at stage B	Actual construction cost
Duration at stage B	Actual construction duration

RCPSP are shown in Table 3. In this phase, the road maintenance unit still has to perform general maintenance operations on the road to maintain normal performance, so there are costs incurred.

TABLE 3. M-stage related parameters.

Parameters of Stage-M	Description
Cost at stage M	Daily expenses during the maintenance period, including personnel costs, cleaning costs, electricity costs, etc.
Duration at stage M	Available years after maintenance

U activities represent the duration of road life cycle stage, where the pavement is beyond its serviceable life after maintenance, which is the stage when the road becomes unserviceable. Due to the nature of the road itself, even if the pavement exceeds its service life and the level of service provided is no longer acceptable to the user, the user can still actually travel on the road, the model reflects this characteristic of the road and sets it as the unserviceable stage, defines the cost to be paid to the user for this stage, and the duration to represent the maximum time allowed at such unserviceable stage. The cost and duration of stage u in terms of RCPSP perspective are shown in Table 4.

TABLE 4. U-stage related parameters.

Parameters of Stage-U	Description
Cost at stage U	Road user cost paid by the road users.
Duration at stage U	The period that the road is allowed to be unavailable, in order to restrict the maximum length of unavailability

In order to control the u stage, the proposed model adopts road user cost to reflect the additional costs that will be incurred when the road becomes unusable, and allows a certain time limit to be set, which also reflects the reality that the road may not be allowed to be unusable for too long.

Regardless of the method chosen by the road maintenance unit to maintain the road section, it will first go through a period of actual construction (i.e., phase b), followed by a period of operational maintenance (i.e., phase m), and then enter the unserviceable stage (i.e., phase u) if the maintenance budget is insufficient for maintenance. Therefore, the ultimate goal of a pavement maintenance strategy is to minimize the chance of all road facility entering phase u status.

C. MODEL FORMULATION

To summarize the basic assumptions of the model in the previous subsection, this subsection introduces the mathematical equations of the proposed model, and the definition of model parameters and variables. IBM ILOG CPLEX Optimizer software and the constraint programming (CP) approach is adopted for model development [58].

This study develops a two-stage integrated optimization model for road maintenance budget planning as depicted in Figure 2, in order to overcome the challenge of insufficient maintenance budget allocation. Model-I (life cycle lifespan evaluation model), which considers the life-cycle lifespan of the overall jurisdictional road sections for maintenance planning, and Model-II (Actual budget adjustment model), which is a budget adjustment model while the approved annual budget is insufficient, these two models can be used interchangeably in different situations in practice. The following subsections will first explain the basic principles, parameters and common constraints of the model, and then explain these two models separately.

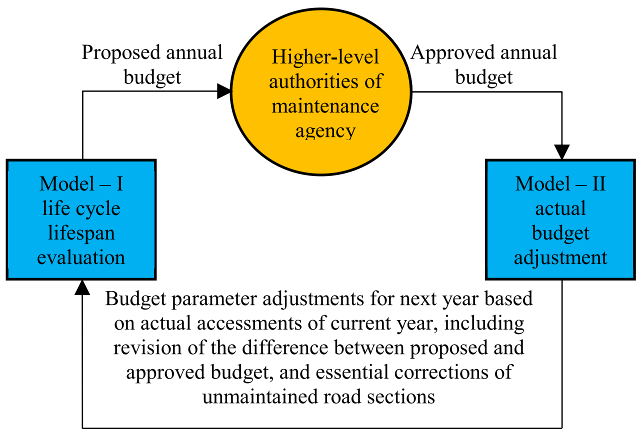

FIGURE 2. Recursive budget adjustment flow in the proposed two-stage integrated optimization model.

For maintenance planning purpose, all road sections are divided into fixed-length road sections and homogeneous road sections. Fixed-length road sections are divided into road units based on the fixed length; homogeneous road sections are divided into units based on the material properties of the road. In this study, we combine the characteristics of homogeneous road sections and fixed-length road sections, and use 1 km as a road unit with a fixed length. In addition, the definition of different maintenance methods in this study is "different maintenance methods regardless of the construction method, as long as the duration and cost are different". For example, even though the road width may not be the same for a unit of 1 kilometer, when the same construction method is used to maintain the road, the duration and cost will be different depending on the width of the road section, which is considered as different maintenance methods. Based on the definition of b, m, and u activity explained earlier, the relevant constraints and the objective function of the model are described below, and the relevant variables and parameters are mentioned in the nomenclature section above.

1) MODEL-I: LIFE CYCLE LIFESPAN EVALUATION MODEL

Model-I adopts the concept of life cycle cost to design the road maintenance strategy, considering that there may be different maintenance methods to choose from. This study acquires the duration and cost of different maintenance methods by examining the historical maintenance data of road facilities and interviewing relevant maintenance staffs. The conceptual solution of model-I, regarding the maintenance time point of each road section and the maintenance method used in the established planning cycle, is as shown in Figure 3. Figure 3 presents a possible result that the maintenance schedule consists of the b, m and u activities, and such activities fills the whole planning cycle through method selection to complete the maintenance planning of each road section life cycle.

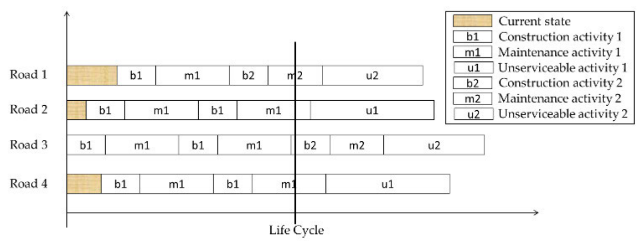

FIGURE 3. **Possible result of model I.**

In general, the maintenance method with higher initial maintenance costs is less expensive to maintain; the maintenance method with lower initial maintenance costs may be more expensive to maintain, in terms of life cycle perspective. In practice, it is crucial for agency managers and road users to ensure that the maximum number of roads are maintained in a usable condition. Therefore, the objective equation of Model-I is shown in Equation (1).

Equation (1) as an objective function intends to maximize the maintenance phase (activity m) that satisfies all the roads in the serviceable condition during the planning cycle without considering the budget limitation. The weight factor of road priority is given to differentiate of the importance of all considered road sections.

Objective function:

$$Max \sum_{n=1}^{y}\sum_{j=1}^{z}\sum_{h=1}^{r}\sum_{i=1}^{t}(W_h \times MD_{hikn}) \tag{1}$$

Constraints:

$$PBS_{hi=0}, \quad \forall h \in SU, \ \forall i \in SI \tag{2}$$

$$(PBE_{hi} = PMS_{hi}), \quad \forall h \in SU, \ \forall i \in SI \tag{3}$$

$$(PME_{hi} = PUS_{hi}), \quad \forall h \in SU, \ \forall i \in SI \tag{4}$$

$$PME_{hi} = PBS_{hi} + dfb, \quad \forall h \in SU, \ \forall i \in SI, \quad dfb \in SD \tag{5}$$

$$PUS_{hi} = PMS_{hi} + dfm, \quad \forall h \in SU, \ \forall i \in SI, \quad dfm \in SD \tag{6}$$

$$\left(PUE_{hi} \le BS_{hi,1}\right) h = 1 \sim r, \quad i = 1 \sim t, \ n = 1 \sim q, \quad j = 1, \ \forall h \in SU, \ \forall i \in SI, \ \forall j \in SM \tag{7}$$

$$(BE_{hikn} = MS_{hikn}), \quad \forall h \in SU, \ \forall i \in SI, \ \forall k \in SM, \quad \forall n \in SM \tag{8}$$

$$(ME_{hikn} = US_{hikn}), \quad \forall h \in SU, \ \forall i \in SI, \ \forall k \in SM, \quad \forall n \in SM \tag{9}$$

$$MS_{hikn} = BS_{hikn} + BD_{hikn}, \quad \forall h \in SU, \ \forall i \in SI, \quad \forall k \in SM, \ \forall n \in SM \tag{10}$$

$$US_{hikn} = MS_{hikn} + MD_{hikn}, \quad \forall h \in SU, \ \forall i \in SI, \quad \forall k \in SM, \ \forall n \in SM \tag{11}$$

$$\left(UD_{hik,n-1} \le BD_{hikn}\right) h{=}1 \sim r, \ i{=}1 \sim t, \quad n{=}2 \sim q, \ j = 1, \ \forall h \in SU, \ \forall i \in SI, \quad \forall j \in SM, \ \forall n \in SM \tag{12}$$

$$\text{If } EX_{hin} = k, \text{ then } (BD_{hikn} = dfb) \text{ and } (MD_{hikn} = dfm) \text{ and } (BC_{hikn} = fcb) \text{ and } (MC_{hikn} = fcm), \quad \forall h \in SU, \ \forall i \in SI, \quad \forall k \in \mathrm{SM}, \ \forall n \in \mathrm{SM} \tag{13}$$

$$\text{If } (UPD_{hik} \neq 0), \text{ then } (UPC_{hik} = fcu), \quad \forall h \in SU, \quad \forall i \in SI, \ \forall k \in SM, \quad \forall fcu \in SC \tag{14}$$

$$\text{If } (UPD_{hik=0}), \text{ then } (UPC_{hik=0}) \text{ and } (PCD_{hi=0}), \quad \forall h \in SU, \ \forall i \in SI, \quad \forall k \in SM \tag{15}$$

$$UPD_{hik} \le dfu, \quad \forall h \in SU, \ \forall i \in SI, \ \forall k \in SM, \quad \forall dfu \in SD \tag{16}$$

$$\text{If } (UD_{hikn} \neq 0), \text{ then } (UC_{hikn} = fcu), \quad \forall h \in SU, \quad \forall i \in SI, \ \forall k \in SM, \quad \forall n \in SM, \ \forall fcu \in SC \tag{17}$$

$$\text{If } (UD_{hikn=0}), \text{ then } (UC_{hikn=0}) \text{ and } (UCD_{hin=0}, \quad \forall h \in SU,)\,, \ \forall i \in SI, \quad \forall k \in SM, \ \forall n \in SM \tag{18}$$

$$UD_{hikn} \le dfu, \quad \forall h \in SU, \ \forall i \in SI, \ \forall k \in SM, \quad \forall n \in SM, \ \forall dfu \in SD \tag{19}$$

$$\sum_{j=1}^{z}\sum_{l=1}^{y}\sum_{i=1}^{t}\sum_{h=1}^{r}(ruf) \ge \sum_{j=1}^{z}\sum_{l=1}^{y}\sum_{i=1}^{t}\sum_{h=1}^{r} \times (PRB_{hik} + PRM_{hik}), \quad \forall h \in SU, \ \forall i \in SI, \quad \forall l \in SY, \ \forall j \in SM, \quad \forall ruf \in SR \tag{20}$$

$$\sum_{j=1}^{z}\sum_{l=1}^{y}\sum_{i=1}^{t}\sum_{h=1}^{r}(rfp) \ge \sum_{j=1}^{z}\sum_{l=1}^{y}\sum_{i=1}^{t}\sum_{h=1}^{r}(PRU_{hik} + PCD_{hik}),$$

$$\forall h \in SU, \quad \forall i \in SI, \quad \forall l \in SY, \quad \forall j \in SM, \ \forall rfp \in SR \tag{21}$$

$$\sum_{j=1}^{z}\sum_{l=1}^{y}\sum_{i=1}^{t}\sum_{h=1}^{r}\sum_{n=1}^{q}(ruf) \geq \sum_{j=1}^{z}\sum_{l=1}^{y}\sum_{i=1}^{t}\sum_{h=1}^{r}\sum_{n=1}^{q}(RFB_{hikn} + RFM_{hikn}),$$
$$\forall h \in SU, \quad \forall i \in SI, \ \forall l \in SY \quad \forall j \in SM, \quad \forall n \in SM, \ \forall ruf \in SR \tag{22}$$

$$\sum_{j=1}^{z}\sum_{l=1}^{y}\sum_{i=1}^{t}\sum_{h=1}^{r}\sum_{n=1}^{q}(rfp) \geq \sum_{j=1}^{z}\sum_{l=1}^{y}\sum_{i=1}^{t}\sum_{h=1}^{r}\sum_{n=1}^{q}(RFU_{hikn} + UCD_{hikn}),$$
$$\forall h \in SU, \ \forall i \in SI, \ \forall l \in SY, \ \forall j \in SM, \quad \forall n \in SM, \ \forall rfp \in SR \tag{23}$$

The further explanation of model I equations (2) to (23) are discussed as follow:

As mentioned above, road statuses are divided into construction phase, operation and maintenance phase, and unserviceable phase, and will be considered as three types of activities. Traditionally equation (2) is employed to establish the schedule, where 0 in this equation pointing as a base point to start the schedule. Equations (3) to (6) establish the relationship between the order of b, m, and u phases in the pavement current state. When the indicator l is equal to 0, it indicates the current condition of the road facility, which is the base data set in the model. Equation (7) specified the first cycle of construction phase (i.e., b activities) in planning time of life cycle starts right after current condition ends.

Equations (8) to (11) establish the relationship between the order of b, m, and u phases on considered time periods of pavement life cycle. Equation (12) indicates that the period of phase u for a road is assigned after the selection of the solution of the subsequent plans. Equation (13) indicates when the model selects a maintenance option for a road section, the corresponding subsequent duration and cost are established based on the maintenance option selected. For example, when the mode selects the k-method maintenance, then the duration and cost for the specific activities are determined simultaneously referring to the k-method.

Equations (14) and (15) represent the relationship between the duration and cost for the current state when the road is in an unusable condition. A similar expression also applied in equations (17) and (18) for the planned life cycle stage that performs after the current state ends. When the road is in an unusable condition, the user cost will be accounted for according to the chosen method. Conversely, if the duration of the unusable stage is zero, the road is in a usable condition. To avoid the long duration of roadway unavailability, the maximum duration is limited by equation (16) for the current state and equation (19) for the planned life cycle stages.

For two different resource caps (i.e. b and m activities), equation (20) in the current state and equation (22) in the planned life cycle stages, respectively indicates that each road section cannot exceed its respective resource cap, e.g., when a road section needs to be worked on and multiple methods are available, the model ensures that multiple methods are not used repeatedly.

Moreover, resource caps for the unserviceable phase (i.e. u activities) respectively defined by equation (21) in the current state and equation (23) in the planned life cycle stages. Both equations indicate when the road is in an unusable status, the cost of the road user cannot exceed the upper limit of the proposed penalty value (ps. the value of indicator l is equal to 0, indicating the current state of the road section).

2) MODEL-II: ACTUAL BUDGET ADJUSTMENT MODEL

In this study, the life-cycle-based budget proposal is generated by Model-I and submitted to the higher level for approval to become the legal budget. However, the actual budget awarded is always cut back due to various factors (e.g., tighter finances for the year). When the actual budget awarded is different from the expected one, the maintenance strategy and its corresponding maintenance method needs be re-adjusted by Model-II. When the next year's budget proposal is submitted, the current status of each road section is realized and input into Model-I to get the future budget plan based on the real situation and submit as the next year's requirements to the higher authorities.

The purpose of Model-II is to solve the problem of rescheduling maintenance activities that were originally scheduled to be maintained. However, when the budget is different from the demand, the maintenance of those road sections needs to be adjusted. The objective formula of Model-II is shown by Equation (24).

The concept of Equation (24) is to create the maximum road service life with the minimum construction, maintenance, and user costs, under budget limitation. The first part represents the importance weight of each road segment, which allows the model to select the road segments that require priority maintenance when the status of each segment is the same, and implicitly uses the magnification factor of the weight to let the model understand that the road segment's serviceability is more important than the maintenance cost. The second part represents the cost of the actual construction phase (i.e., phase b), the third part represents the cost of the maintenance phase (i.e., phase m), and the fourth part represents the cost of the road unserviceable phase (i.e., phase u). By deducting the cost of each stage, the model can select the most economical solution.

In model-II, we consider the road sections that require direct maintenance and focus on the ones that need immediate rehabilitation. Therefore, instead of evaluating from a life cycle perspective, we select the method that has the longest effective duration for each road section with the consideration of the road importance priority and budget limitation. In other words, this model only needs to consider the road sections that need immediate maintenance (i.e., the road has entered the unserviceable phase), evaluate the selection of road sections and maintenance methods, and schedule maintenance activities for the next year based on the budget issued in the following year. Therefore, the formulation of model-II requires some adjustments as follows.

Objective Function:

$$Max \sum_{j=1}^{z}\sum_{l=1}^{y}\sum_{i=1}^{t}\sum_{h=1}^{r}\sum_{n=1}^{q} MRY_{hikn}\left(W_h \times MDY_{hikn}\right) - \sum_{j=1}^{z}\sum_{l=1}^{y}\sum_{i=1}^{t}\sum_{h=1}^{r}\sum_{n=1}^{q}(BCY_{hikn} \times dfb) + (MCY_{hikn} \times dfm) - \sum_{j=1}^{z}\sum_{l=1}^{y}\sum_{i=1}^{t}\sum_{h=1}^{r}\sum_{n=1}^{q}(UDY_{hikn} \times fcu) \quad (24)$$

Constraint:

$$BSY_{hikn} = 0, \quad \forall h \in SU, \ \forall i \in SI, \ \forall k \in SM, \quad \forall n \in SM \quad (25)$$

$$MSY_{hikn} = BSY_{hikn} + BDY_{hikn}, \ \forall h \in SU, \ \forall i \in SI, \quad \forall k \in SM, \ \forall n \in SM \quad (26)$$

$$USY_{hikn} = MSY_{hikn} + MDY_{hikn}, \ \forall h \in SU, \quad \forall i \in SI, \ \forall k \in SM, \ \forall n \in SM \quad (27)$$

$$\text{If } (YF_{hikn} = 1), \text{ then } (BDY_{hikn} = dfb) \text{ and } (BCY_{hikn} = fcb), \ \forall h \in SU, \ \forall i \in SI, \quad \forall k \in SM, \ \forall n \in SM, \ \forall dfb \in SM, \quad \forall fcb \in SC \quad (28)$$

$$\text{If } (YF_{hikn} = 1), \text{ then } (MDY_{hikn} = dfm) \text{ and } (MCY_{hikn} = fcm), \quad \forall h \in SU, \ \forall i \in SI, \quad \forall k \in SM, \ \forall n \in SM, \ \forall dfm \in SM, \quad \forall fcm \in SC \quad (29)$$

$$\text{If } (YF_{hikn} = 1), \text{ then } (UDY_{hikn} = dfu) \text{ and } (UCY_{hikn} = fcu), \quad \forall h \in SU, \ \forall i \in SI, \quad \forall k \in SM, \ \forall n \in SM, \ \forall dfu \in SM, \quad \forall fcu \in SC \quad (30)$$

$$\text{If } (YF_{hikn=0}), \text{ then } (BDY_{hikn=0}) \text{ and } (BCY_{hikn=0}), \ \forall h \in SU, \ \forall i \in SI, \quad \forall k \in SM, \ \forall n \in SM \quad (31)$$

$$\text{If } (YF_{hikn=0}), \text{ then } (MDY_{hikn=0}) \text{ and } (MCY_{hikn=0}), \quad \forall h \in SU, \ \forall i \in SI, \quad \forall k \in SM, \ \forall n \in SM, \quad (32)$$

$$\text{If } (YF_{hikn=0}), \text{ then } (UDY_{hikn=0}) \text{ and } (UCY_{hikn=0}), \quad \forall h \in SU, \ \forall i \in SI, \quad \forall k \in SM, \ \forall n \in SM, \quad (33)$$

$$(rab) \geq \sum_{j=1}^{z}\sum_{l=1}^{y}\sum_{i=1}^{t}\sum_{h=1}^{r}\sum_{n=1}^{q} \times (BCY_{hikn} + MCY_{hikn}), \quad \forall h \in SU, \ \forall i \in SI, \quad \forall k \in SM, \ \forall l \in SY, \ \forall n \in SM, \quad rab \in SR \quad (34)$$

$$\sum_{j=1}^{z}\sum_{l=1}^{y}\sum_{i=1}^{t}\sum_{h=1}^{r}\sum_{n=1}^{q}(rfp) \geq \sum_{j=1}^{z}\sum_{l=1}^{y}\sum_{i=1}^{t}\sum_{h=1}^{r}\sum_{n=1}^{q}(UCY_{hikn}), \quad \forall h \in SU, \quad \forall i \in SI, \ \forall k \in SM, \ \forall l \in SY, \quad \forall n \in SM, \ rab \in SR \quad (35)$$

$$\sum_{j=1}^{z}\sum_{l=1}^{y}\sum_{i=1}^{t}\sum_{h=1}^{r}\sum_{n=1}^{q}(ruf) \geq \sum_{j=1}^{z}\sum_{l=1}^{y}\sum_{i=1}^{t}\sum_{h=1}^{r}\sum_{n=1}^{q} (BRY_{hikn} + MRY_{hikn} + URY_{hikn}), \quad \forall h \in SU, \ \forall i \in SI, \ \forall k \in SM, \ \forall l \in SY, \quad \forall n \in SM, \ ruf \in SR \quad (36)$$

Moreover, the explanation of model II, equations (25) to (35), is discussed as follow:

Equation (25) is specified as starting point to establish the maintenance schedule with the initial time equal to 0. Subsequently, equations (26) and (27) are established to ensures that the three phases will be selected, as well as ending by an unserviceable phase (i.e., u activity).

Equations (28) to (30) respectively describe when on a road there is a selected maintenance plan at operation b, operation m, and operation u, then the maintenance duration and maintenance cost will be accounted into the model calculation. Where the $YF_{hikn} = 1$ on those equations indicates that the road resources are being utilized. Conversely, equations (31) to (33) respectively describe if there is no maintenance plan selected at b, m, and u phase, then the maintenance duration and cost does not require. Where the $YF_{hikn} = 0$ on those equations indicates that there are no road resources are being utilized.

Equation (34) indicates that the sum of the operation costs spent in all the phases is not allowable to exceed the specified maintenance budget. Equation (35) indicates that the maximum total cost of the road user in the unserviceable phase is equal to the proposed penalty value. Consider the limitation of available resources, equation (36) specify if the total amount of road resources for all operations cannot exceed the original road resources ceiling.

IV. CASE ANALYSIS AND DISCUSSION

The datasets of case study were collected and several expert interviews were conducted with the Dounan Public Works Section of the Fifth District Maintenance Engineering Office of the General Highway Bureau, Taiwan Ministry of Transportation and Communications. This road maintenance unit was in charge of three types of road widths in 2019, and the number of road sections of each type of road width

TABLE 5. Maintenance option information.

Road width (Meter)	Section quantity (Km)	Asphalt Concrete	Recycled Asphalt Concrete
7.4	5	Construction cost: 32 ($10 thousands /km/year) Construction duration: 1 year Maintenance cost: 6 ($10 thousands /km/ year) Maintenance duration: 4 year Unserviceable duration: 20 year	Construction cost: 20 ($10 thousands /km/year) Construction duration: 1 year Maintenance cost: 13 ($10 thousands /km/year) Maintenance duration: 3 year Unserviceable duration: 20 year
14.2	7	Construction cost: 55 ($10 thousands /km/ year) Construction duration: 1 year Maintenance cost: 10 ($10 thousands /km/ year) Maintenance duration: 4 year Unserviceable duration: 20 year	Construction cost: 32 ($10 thousands /km/ year) Construction duration: 1 year Maintenance cost: 23 ($10 thousands /km/year) Maintenance duration: 3 year Unserviceable duration: 20 year
20	12	Construction cost: 74 ($10 thousands /km/ year) Construction duration: 1 year Maintenance cost: 15 ($10 thousands /km/ year) Maintenance duration: 4 year Unserviceable duration: 20 year	Construction cost: 42 ($10 thousands /km/year) Construction duration: 1 year Maintenance cost: 34 ($10 thousands /km/year) Maintenance duration: 3 year Unserviceable duration: 20 year

was 5, 7, and 12 in meters respectively, totaling 24 sections. There are two different maintenance methods to choose from, the duration and cost of two maintenance options are shown in Table 5. In this case, the construction period of less than one year is also regarded as one year because most of the road maintenance construction periods will not exceed one year, and from the perspective of budgeting, only the current year's maintenance budget needs to be reflected.

The road user cost is defined according to the importance of each road section based on the data in Table 6, when the importance of the road section is 1, road user cost is $ 30 million; when the importance of the road section is 2, road user cost is $ 20 million; when the importance of the road section is 3, road user cost is $ 10 million.

Table 7 shows the current status of maintenance option of each road section in 2019 and the maintenance methods used. 10 road sections are in the operation and maintenance stage, 3 road sections are in Class 4, i.e., in poor condition but passable, and 11 road sections are in urgent need of construction and maintenance by road maintenance units.

TABLE 6. Road section importance.

Section No	Importance	Section No	Importance	Section No	Importance
1	3	9	2	17	1
2	3	10	1	18	1
3	3	11	1	19	1
4	1	12	1	20	2
5	1	13	1	21	2
6	3	14	1	22	1
7	2	15	2	23	2
8	2	16	2	24	2

TABLE 7. Current status information.

Road width (Meter)	Section No	Remaining service life (years)	Maintenance option
7.4	1	3	Asphalt Concrete
	2	4	Asphalt Concrete
	3	-	Wait for maintenance
	4	-	Wait for maintenance
	5	-	Wait for maintenance
14.2	6	-	Wait for maintenance
	7	-	Wait for maintenance
	8	-	Wait for maintenance
	9	1	Asphalt Concrete
	10	2	Recycled Asphalt Concrete
	11	2	Recycled Asphalt Concrete
	12	1	Asphalt Concrete
20	13	1	Recycled Asphalt Concrete
	14	2	Recycled Asphalt Concrete
	15	1	Recycled Asphalt Concrete
	16	1	Asphalt Concrete
	17	3	Asphalt Concrete
	18	4	Asphalt Concrete
	19	4	Asphalt Concrete
	20	-	Wait for maintenance
	21	-	Wait for maintenance
	22	-	Wait for maintenance
	23	-	Wait for maintenance
	24	-	Wait for maintenance

A. VALIDATION OF MODEL-I IN 2019

If there's no budget limitation, the proposed model intends to maximize the overall maintenance efficiency, and satisfy the objective that all road sections are properly maintained to achieve the maximum service lifespan and not in an unusable condition. Therefore, Model-I selects the most efficient and economical fresh asphalt for each road section within the road maintenance unit, as shown in Figure 4. The road maintenance unit chooses the most cost-effective fresh asphalt concrete method to fill the entire planning cycle, which is in line with the expected results of this study.

Based on the scheduling results obtained from Figure 4, we can calculate the budget demand for each subsequent year, based on as annual total expenses shown in Table 8, we can

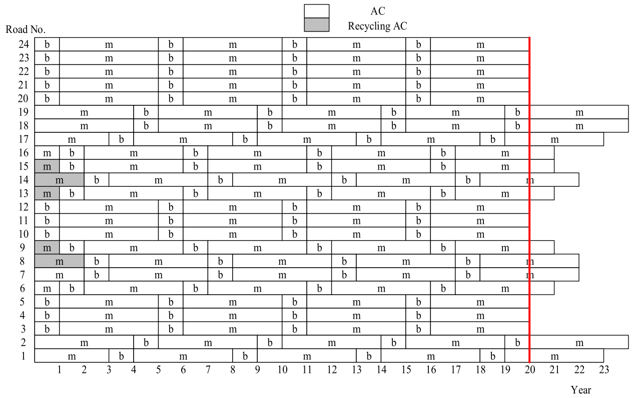

FIGURE 4. Optimization result of model I.

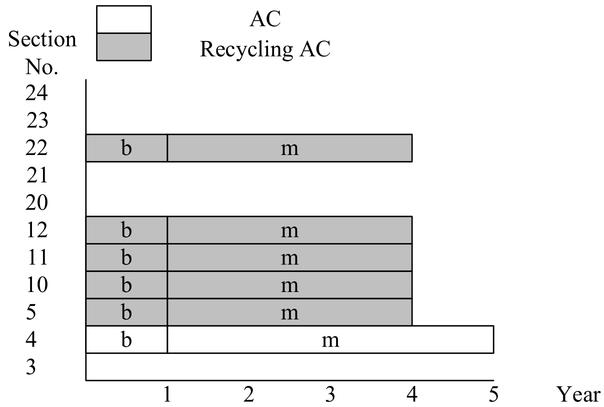

FIGURE 5. Optimization result of model II in 2019 (budget: 1.9 million).

TABLE 8. Annual total expenses (model-I).

Year	Annual total expense (thousand USD)	Year	Annual total expense (thousand USD)	Year	Annual total expense (thousand USD)
1	871	9	365	17	547
2	524	10	424	18	429
3	429	11	788	19	365
4	365	12	547	20	424
5	424	13	429		
6	788	14	365		
7	547	15	424		
8	429	16	788		

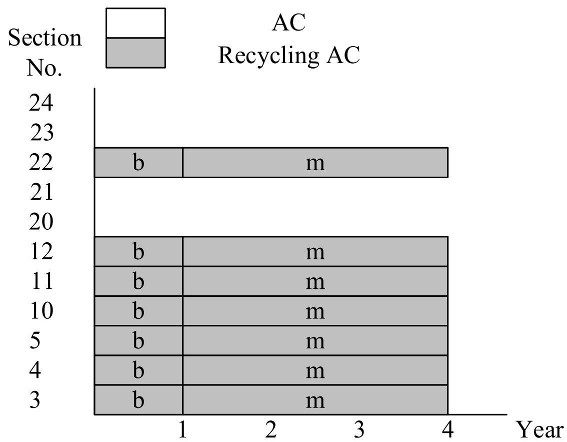

FIGURE 6. Optimization result of model II in 2019 (budget: 2.0 million).

observe that the budget demand is highest in the first year of the planning cycle, $ 8.71 million, and the budget for the first two years is irregular due to the different conditions of each road section, and the budget from the third year onwards is in a regular pattern every five years.

B. VALIDATION OF MODEL-II IN 2019

In 2019, the real situation of budget approval is not as ideal as the planned result of model I. The annual maintenance budget allocated to the road maintenance unit is $ 4.3 million, and the remaining maintenance budget is $ 1.9 million after deducting the operation and maintenance activities, because the approved budget is insufficient, it is impossible to carry out maintenance work according to the result previously obtained from Model-I. At this time, we use Model-II to evaluate and rearrange the maintenance schedule of the currently unserviceable road sections, and the result is shown in Figure 5.

Thus, it can be found that when the budget is insufficient to maintain all the sections that must be maintained at the same time, Model-II considered the importance of 11 sections and the costs and benefits of different maintenance methods, and selected 6 sections with higher importance for maintenance first, and adjusted 5 of them to be maintained with recycled asphalt concrete method which is different than original fresh asphalt concrete method, due to budget shortage.

TABLE 9. Updated road status for two road sections in 2019.

Section No	Current status description
8	Rapidly deteriorating condition, service life reduced to 1 year
15	Unserviceable status

To verify the flexibility and applicability of Model-II, the available budget was revised upward to $ 2 million, at which point the result of Model-II is shown in Figure 6. It can be found that after adjusting the maintenance of section 4 to recycled asphalt concrete method, it is sufficient to support the maintenance cost of section 3, and the rescheduling makes good use of the remaining budget to achieve the benefit of making more sections to undertake maintenance action in line with the original schedule.

C. INTEGRATED SOLUTION OF BOTH MODELS IN 2020

In 2019, some of the road sections under the responsibility of the road maintenance unit suffered from certain natural disasters, resulting in the impairment of their service life, and their actual conditions are shown in Table 9.

TABLE 10. Current maintenance status of road sections in 2020.

Road width (Meter)	Section No	Remaining service life (years)	Maintenance option
	1	2	Asphalt Concrete
	2	3	Asphalt Concrete
7.4	3	-	Wait for maintenance
	4	4	Asphalt Concrete
	5	3	Recycled Asphalt Concrete
	6	-	Wait for maintenance
	7	1	Asphalt Concrete
	8	1	Recycled Asphalt Concrete
14.2	9	-	Wait for maintenance
	10	3	Recycled Asphalt Concrete
	11	3	Recycled Asphalt Concrete
	12	3	Recycled Asphalt Concrete
	13	-	Wait for maintenance
	14	1	Recycled Asphalt Concrete
	15	-	Wait for maintenance
	16	-	Wait for maintenance
	17	2	Asphalt Concrete
	18	3	Asphalt Concrete
20	19	3	Asphalt Concrete
	20	-	Wait for maintenance
	21	-	Wait for maintenance
	22	3	Wait for maintenance
	23	-	Wait for maintenance
	24	-	Wait for maintenance

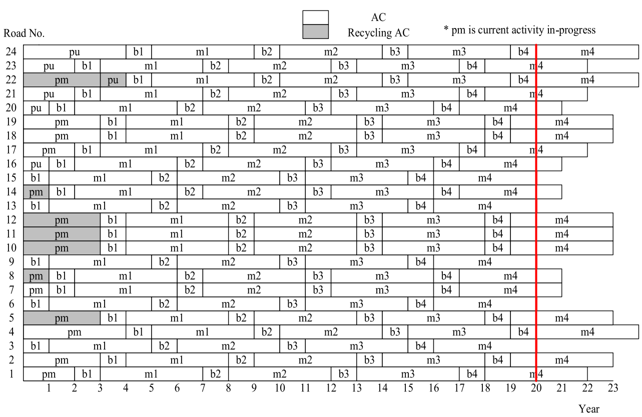

FIGURE 7. Adjusted maintenance schedule of model-I in 2020.

Therefore, after the maintenance actions in 2019, the current physical conditions for all road sections in 2020 are shown in Table 10.

The approved maintenance budget for 2020 is $ 6 million, and after the calculation through Model-II, the actual road data in the above table was input into Model-I to re-evaluate the future maintenance budget planning, and the new road maintenance schedule is shown in Figure 7.

From Figure 7, we can get the estimated demand amount for each subsequent year in the planning cycle of 20 years as shown in Table 11, and we need to know that the cost of road

TABLE 11. Annual total expenses in 2020 projection (model-I).

Year	Annual total expense (thousand USD)	Year	Annual total expense (thousand USD)	Year	Annual total expense (thousand USD)
1	536	9	208	17	194
2	567	10	150	18	171
3	533	11	182	19	208
4	555	12	194	20	150
5	424	13	171		
6	514	14	208		
7	547	15	150		
8	483	16	182		

users due to the unavailability of roads is $ 10,000, $ 6,000, $ 2,000, and $ 5,000 (in 10 thousands) from year 1 to year 4 respectively.

Through the integration work of the two models, it is easy to find the appropriate road maintenance schedule to meet the budget requirement and budget shortage situations faced by maintenance agencies in a real world. The maintenance strategy suggested by the proposed research helps them to grasp the current status of their roads, and furthermore, predicts the future status of the roads in charge.

V. COCLUSION AND RECOMMENDATIONS

In the study, we propose an integrated two-stage optimization model to deal with life cycle pavement maintenance budgeting problems, where two models are developed. Model-I provides a maximum lifespan solution for road maintenance schedule from a life cycle perspective, while Model-II is carried out for the budget adjustment purpose when the actual budget approved is not as expected. The integration of these two models provides a basic framework of budget planning for road maintenance units, and the following achievements are validated through actual case analysis.

1. Based on the scheduling results of the proposed model, the road maintenance unit can predict the annual maintenance situation of each road section and calculate the demand for future annual road maintenance budget, which provides the maintenance unit with the function of early warning and maintenance activities compared with the traditional way of arranging maintenance only when road pavement damages occur.
2. The proposed model considers the road importance priority and achieves the maximum usage of all considered road sections with the least cost of maintenance and road user. In addition, the maintenance arrangement can be adjusted when the budget is not as expected, and as many road sections as possible can be maintained in a serviceable condition through the selection of various maintenance options.
3. By integrating the outcomes of these two models, maintenance units can re-evaluate and propose the next year's budget request according to the current situation, and

provide maintenance unit a mechanism to react to the budget shortage early.

Based on the basic assumptions of this study and the difficulties encountered during the study, the following suggestions are recommended to conduct a follow-up investigation.

1. Since the study model only considers the serviceability of the road section without considering other benefits, such as tourism benefits, environmental aesthetics, etc., brought about by road rehabilitation, these additional benefits are also part of the life cycle cost, but because they are not easy to quantify, they are ignored in this study to establish the budget allocation model for road facility maintenance. It can be further considered so that the analysis and evaluation of the model can be more objective by considering various aspects.
2. This study introduces the concept of life cycle into the road assessment model by using the historical data of road maintenance units and the experience of road maintenance personnel as the criteria for assessing the road life cycle, however, the historical data of road maintenance units are generally insufficient or the maintenance data have only been archived and stored in recent years. Therefore, this evaluation method can only estimate the approximate road life cycle at this stage, but cannot conduct accurate evaluation. A more advanced evaluation method should be developed and tested for better assessment on maintenance data.
3. This study assumes that all road sections are homogeneous sections of fixed length, with the same geographical conditions and similar types of traffic, but in real practices, there are still some differences.

REFERENCES

[1] B. Yu, Q. Lu, and J. Xu, "An improved pavement maintenance optimization methodology: Integrating LCA and LCCA," *Transp. Res. A, Policy Pract.*, vol. 55, pp. 1–11, Sep. 2013, doi: 10.1016/j.tra.2013.07.004.

[2] F. Kong and D. Dou, "RCPSP with combined precedence relations and resource calendars," *J. Construct. Eng. Manage.*, vol. 146, no. 12, Sep. 2020, Art. no. 04020133, doi: 10.1061/(asce)co.1943-7862.0001929.

[3] F. Nascimento, B. Gouveia, F. Dias, F. Ribeiro, and M. A. Silva, "A method to select a road pavement structure with life cycle assessment," *J. Cleaner Prod.*, vol. 271, Oct. 2020, Art. no. 122210, doi: 10.1016/j.jclepro.2020.122210.

[4] K. D. Kuhn and S. M. Madanat, "Model uncertainty and the management of a system of infrastructure facilities," *Transp. Res. C, Emerg. Technol.*, vol. 13, nos. 5–6, pp. 391–404, Oct. 2005, doi: 10.1016/j.trc.2006.02.001.

[5] M. G. Augeri, S. Greco, and V. Nicolosi, "Planning urban pavement maintenance by a new interactive multiobjective optimization approach," *Eur. Transp. Res. Rev.*, vol. 11, no. 1, pp. 1–14, Mar. 2019, doi: 10.1186/s12544-019-0353-9.

[6] P. L. Durango-Cohen and S. M. Madanat, "Optimization of inspection and maintenance decisions for infrastructure facilities under performance model uncertainty: A quasi-Bayes approach," *Transp. Res. A, Policy Pract.*, vol. 42, no. 8, pp. 1074–1085, Oct. 2008, doi: 10.1016/j.tra.2008.03.004.

[7] K. D. Kuhn, "Pavement network maintenance optimization considering multidimensional condition data," *J. Infrastruct. Syst.*, vol. 18, no. 4, pp. 270–277, Dec. 2012, doi: 10.1061/(asce)is.1943-555x.0000077.

[8] A. Medury and S. Madanat, "Incorporating network considerations into pavement management systems: A case for approximate dynamic programming," *Transp. Res. C, Emerg. Technol.*, vol. 33, pp. 134–150, Aug. 2013, doi: 10.1016/j.trc.2013.03.003.

[9] A. Medury and S. Madanat, "Simultaneous network optimization approach for pavement management systems," *J. Infrastruct. Syst.*, vol. 20, no. 3, Sep. 2014, Art. no. 04014010, doi: 10.1061/(asce)is.1943-555x.0000149.

[10] J. Lee and S. Madanat, "Jointly optimal policies for pavement maintenance, resurfacing and reconstruction," *EURO J. Transp. Logistics*, vol. 4, no. 1, pp. 75–95, Mar. 2015, doi: 10.1007/s13676-014-0065-1.

[11] H. Zhang, G. A. Keoleian, M. D. Lepech, and A. Kendall, "Life-cycle optimization of pavement overlay systems," *J. Infrastruct. Syst.*, vol. 16, no. 4, pp. 310–322, Dec. 2010, doi: 10.1061/(asce)is.1943-555x.0000042.

[12] M. Huang, Q. Dong, F. Ni, and L. Wang, "LCA and LCCA based multi-objective optimization of pavement maintenance," *J. Cleaner Prod.*, vol. 283, Feb. 2021, Art. no. 124583, doi: 10.1016/j.jclepro.2020.124583.

[13] I.-L. Wang, Y.-C.-J. Tsai, and F. Li, "A network flow model for clustering segments and minimizing total maintenance and rehabilitation cost," *Comput. Ind. Eng.*, vol. 60, no. 4, pp. 593–601, May 2011, doi: 10.1016/j.cie.2011.01.001.

[14] F. Guo, J. Gregory, and R. Kirchain, "Incorporating cost uncertainty and path dependence into treatment selection for pavement networks," *Transp. Res. C, Emerg. Technol.*, vol. 110, pp. 40–55, Jan. 2020, doi: 10.1016/j.trc.2019.11.015.

[15] Y. Shi, Y. Xiang, H. Xiao, and L. Xing, "Joint optimization of budget allocation and maintenance planning of multi-facility transportation infrastructure systems," *Eur. J. Oper. Res.*, vol. 288, no. 2, pp. 382–393, Jan. 2021, doi: 10.1016/j.ejor.2020.05.050.

[16] J. C. Chu and K.-H. Huang, "Mathematical programming framework for modeling and comparing network-level pavement maintenance strategies," *Transp. Res. B, Methodol.*, vol. 109, pp. 1–25, Mar. 2018, doi: 10.1016/j.trb.2018.01.005.

[17] Y. Ouyang and S. Madanat, "Optimal scheduling of rehabilitation activities for multiple pavement facilities: Exact and approximate solutions," *Transp. Res. A, Policy Pract.*, vol. 38, no. 5, pp. 347–365, Jun. 2004, doi: 10.1016/j.tra.2003.10.007.

[18] Y. Ouyang and S. Madanat, "An analytical solution for the finite-horizon pavement resurfacing planning problem," *Transp. Res. B, Methodol.*, vol. 40, no. 9, pp. 767–778, Nov. 2006, doi: 10.1016/j.trb.2005.11.001.

[19] J. Lee and S. Madanat, "A joint bottom-up solution methodology for system-level pavement rehabilitation and reconstruction," *Transp. Res. B, Methodol.*, vol. 78, pp. 106–122, Aug. 2015, doi: 10.1016/j.trb.2015.05.001.

[20] T. F. Fwa, W. T. Chan, and K. Z. Hoque, "Multiobjective optimization for pavement maintenance programming," *J. Transp. Eng.*, vol. 126, no. 5, pp. 367–374, Sep. 2000.

[21] P. Lu and D. Tolliver, "Multiobjective pavement-preservation decision making with simulated constraint boundary programming," *J. Transp. Eng.*, vol. 139, no. 9, pp. 880–888, Sep. 2013, doi: 10.1061/(ASCE)TE.1943-5436.0000573.

[22] R. Denysiuk, A. V. Moreira, J. C. Matos, J. R. M. Oliveira, and A. Santos, "Two-stage multiobjective optimization of maintenance scheduling for pavements," *J. Infrastruct. Syst.*, vol. 23, no. 3, Sep. 2017, Art. no. 04017001, doi: 10.1061/(asce)is.1943-555x.0000355.

[23] A. K. Khiavi and H. Mohammadi, "Multiobjective optimization in pavement management system using NSGA-II method," *J. Transp. Eng., B, Pavements*, vol. 144, no. 2, Jun. 2018, Art. no. 04018016, doi: 10.1061/JPEODX.0000041.

[24] B. Yu, X. Gu, F. Ni, and R. Guo, "Multi-objective optimization for asphalt pavement maintenance plans at project level: Integrating performance, cost and environment," *Transp. Res. D, Transp. Environ.*, vol. 41, pp. 64–74, Dec. 2015, doi: 10.1016/j.trd.2015.09.016.

[25] R. Cao, Z. Leng, J. Yu, and S.-C. Hsu, "Multi-objective optimization for maintaining low-noise pavement network system in Hong Kong," *Transp. Res. D, Transp. Environ.*, vol. 88, Nov. 2020, Art. no. 102573, doi: 10.1016/j.trd.2020.102573.

[26] J.-S. Chou and T.-S. Le, "Reliability-based performance simulation for optimized pavement maintenance," *Rel. Eng. Syst. Saf.*, vol. 96, no. 10, pp. 1402–1410, Oct. 2011, doi: 10.1016/j.ress.2011.05.005.

[27] K. Ahmed, B. Al-Khateeb, and M. Mahmood, "Application of chaos discrete particle swarm optimization algorithm on pavement maintenance scheduling problem," *Cluster Comput.*, vol. 22, no. S2, pp. 4647–4657, Mar. 2019, doi: 10.1007/s10586-018-2239-3.

[28] N. Sathaye and S. Madanat, "A bottom-up solution for the multi-facility optimal pavement resurfacing problem," *Transp. Res. B, Methodol.*, vol. 45, no. 7, pp. 1004–1017, Aug. 2011, doi: 10.1016/j.trb.2011.03.002.

[29] W. Gu, Y. Ouyang, and S. Madanat, "Joint optimization of pavement maintenance and resurfacing planning," *Transp. Res. B, Methodol.*, vol. 46, no. 4, pp. 511–519, May 2012, doi: 10.1016/j.trb.2011.12.002.

[30] J. C. Chu and Y.-J. Chen, "Optimal threshold-based network-level transportation infrastructure life-cycle management with heterogeneous maintenance actions," *Transp. Res. B, Methodol.*, vol. 46, no. 9, pp. 1123–1143, Nov. 2012, doi: 10.1016/j.trb.2012.05.002.

[31] L. Zhang, L. Fu, W. Gu, Y. Ouyang, and Y. Hu, "A general iterative approach for the system-level joint optimization of pavement maintenance, rehabilitation, and reconstruction planning," *Transp. Res. B, Methodol.*, vol. 105, pp. 378–400, Nov. 2017, doi: 10.1016/j.trb.2017.09.014.

[32] P. Hankach, T. Lorino, and P. Gastineau, "A constraint-based, efficiency optimisation approach to network-level pavement maintenance management," *Struct. Infrastruct. Eng.*, vol. 15, no. 11, pp. 1450–1467, Jun. 2019, doi: 10.1080/15732479.2019.1624787.

[33] C. Torres-Machi, E. Pellicer, V. Yepes, and A. Chamorro, "Towards a sustainable optimization of pavement maintenance programs under budgetary restrictions," *J. Cleaner Prod.*, vol. 148, pp. 90–102, Apr. 2017, doi: 10.1016/j.jclepro.2017.01.100.

[34] J. M. Vassallo and R. Izquierdo, "Modeling road maintenance management and financing," *J. Transp. Eng.*, vol. 128, no. 6, pp. 559–567, Nov. 2002, doi: 10.1061/(ASCE)0733-947X(2002)128:6(559).

[35] S. Labi and K. C. Sinha, "Life-cycle evaluation of flexible pavement preventive maintenance," *J. Transp. Eng.*, vol. 131, no. 10, pp. 744–751, Oct. 2005, doi: 10.1061/(ASCE)0733-947X(2005)131:10(744).

[36] Y. Yoon, H. Shah, M. Hastak, and J. Lee, "Leveling process of annual budgetary requirements for pavement preservation," *J. Infrastruct. Syst.*, vol. 20, no. 1, Mar. 2014, Art. no. 04013004, doi: 10.1061/(asce)is.1943-555x.0000140.

[37] G. Heravi and A. N. Esmaeeli, "Fuzzy multicriteria decision-making approach for pavement project evaluation using life-cycle cost/performance analysis," *J. Infrastruct. Syst.*, vol. 20, no. 2, Jun. 2014, Art. no. 04014002, doi: 10.1061/(asce)is.1943-555x.0000170.

[38] X. Zheng, S. M. Easa, Z. Yang, T. Ji, and Z. Jiang, "Life-cycle sustainability assessment of pavement maintenance alternatives: Methodology and case study," *J. Cleaner Prod.*, vol. 213, pp. 659–672, Mar. 2019, doi: 10.1016/j.jclepro.2018.12.227.

[39] C. Torres-Machi, A. Osorio-Lird, A. Chamorro, C. Videla, S. L. Tighe, and C. Mourgues, "Impact of environmental assessment and budgetary restrictions in pavement maintenance decisions: Application to an urban network," *Transp. Res. D, Transp. Environ.*, vol. 59, pp. 192–204, Mar. 2018, doi: 10.1016/j.trd.2017.12.017.

[40] Z. Han, J. D. Porras-Alvarado, C. Stone, and Z. Zhang, "Incorporating uncertainties into determination of flexible pavement preventive maintenance interval," *Transportmetrica A, Transp. Sci.*, vol. 15, no. 1, pp. 34–54, Feb. 2019, doi: 10.1080/23249935.2018.1433730.

[41] M. Hafez, K. Ksaibati, and R. A. Atadero, "Optimizing expert-based decision-making of pavement maintenance using artificial neural networks with pattern-recognition algorithms," *Transp. Res. Rec., J. Transp. Res. Board*, vol. 2673, no. 11, pp. 90–100, Nov. 2019, doi: 10.1177/0361198119851085.

[42] D. Han and M. Do, "Life cycle cost analysis on pavement inspection intervals considering maintenance work delay," *KSCE J. Civil Eng.*, vol. 19, no. 6, pp. 1716–1726, Sep. 2015, doi: 10.1007/s12205-014-1229-0.

[43] Z. Wang and H. Wang, "Life-cycle cost analysis of optimal timing of pavement preservation," *Frontiers Struct. Civil Eng.*, vol. 11, no. 1, pp. 17–26, Mar. 2017, doi: 10.1007/s11709-016-0369-3.

[44] K. A. Abaza, "Empirical Markovian-based models for rehabilitated pavement performance used in a life cycle analysis approach," *Struct. Infrastruct. Eng.*, vol. 13, no. 5, pp. 625–636, May 2017, doi: 10.1080/15732479.2016.1187180.

[45] M. Onyango, S. A. Merabti, J. Owino, I. Fomunung, and W. Wu, "Analysis of cost effective pavement treatment and budget optimization for arterial roads in the city of Chattanooga," *Frontiers Struct. Civil Eng.*, vol. 12, no. 3, pp. 291–299, Sep. 2018, doi: 10.1007/s11709-017-0419-5.

[46] A. Braham, "Comparing life-cycle cost analysis of full-depth reclamation versus traditional pavement maintenance and rehabilitation strategies," *Transp. Res. Rec., J. Transp. Res. Board*, vol. 2573, no. 1, pp. 49–59, Jan. 2016, doi: 10.3141/2573-07.

[47] J. Santos, J. Bryce, G. Flintsch, A. Ferreira, and B. Diefenderfer, "A life cycle assessment of in-place recycling and conventional pavement construction and maintenance practices," *Struct. Infrastruct. Eng.*, vol. 11, no. 9, pp. 1199–1217, Sep. 2015, doi: 10.1080/15732479.2014.945095.

[48] J. France-Mensah and W. J. O'Brien, "Budget allocation models for pavement maintenance and rehabilitation: Comparative case study," *J. Manage. Eng.*, vol. 34, no. 2, Mar. 2018, Art. no. 05018002, doi: 10.1061/(asce)me.1943-5479.0000599.

[49] S. Hartmann and D. Briskorn, "A survey of variants and extensions of the resource-constrained project scheduling problem," *Eur. J. Oper. Res.*, vol. 207, no. 1, pp. 1–14, Nov. 2010, doi: 10.1016/j.ejor.2009.11.005.

[50] Z. Hanzálek and P. Šůcha, "Time symmetry of resource constrained project scheduling with general temporal constraints and take-give resources," *Ann. Oper. Res.*, vol. 248, nos. 1–2, pp. 209–237, Jan. 2017, doi: 10.1007/s10479-016-2184-6.

[51] R. K. Chakrabortty, R. A. Sarker, and D. L. Essam, "Resource constrained project scheduling with uncertain activity durations," *Comput. Ind. Eng.*, vol. 112, pp. 537–550, Oct. 2017, doi: 10.1016/j.cie.2016.12.040.

[52] R. K. Chakrabortty, H. F. Rahman, K. M. A. Haque, S. K. Paul, and M. J. Ryan, "An event-based reactive scheduling approach for the resource constrained project scheduling problem with unreliable resources," *Comput. Ind. Eng.*, vol. 151, Jan. 2021, Art. no. 106981, doi: 10.1016/j.cie.2020.106981.

[53] E. Oztemel and A. A. Selam, "Bees algorithm for multi-mode, resource-constrained project scheduling in molding industry," *Comput. Ind. Eng.*, vol. 112, pp. 187–196, Oct. 2017, doi: 10.1016/j.cie.2017.08.012.

[54] J. Liu, Y. Liu, Y. Shi, and J. Li, "Solving resource-constrained project scheduling problem via genetic algorithm," *J. Comput. Civil Eng.*, vol. 34, no. 2, Mar. 2020, Art. no. 04019055, doi: 10.1061/(ASCE)CP.1943-5487.0000874.

[55] F. Abbondati, S. A. Biancardo, R. Veropalumbo, and G. Dell'Acqua, "Surface monitoring of road pavements using mobile crowdsensing technology," *Measurement*, vol. 171, Feb. 2021, Art. no. 108763, doi: 10.1016/j.measurement.2020.108763.

[56] J. M. Pinatt, M. L. Chicati, J. S. Ildefonso, and C. R. G. D. Filetti, "Evaluation of pavement condition index by different methods: Case study of Maringá, Brazil," *Transp. Res. Interdiscipl. Perspect.*, vol. 4, Mar. 2020, Art. no. 100100, doi: 10.1016/j.trip.2020.100100.

[57] *AASHTO Maintenance Manual for Roadways and Bridges*, Amer. Assoc. State Highway Transp. Officials, Washington, DC, USA, 2007.

[58] IBM. (2021). *IBM ILOG CPLEX Optimization Studio*. North Castle, NY, USA. [Online]. Available: https//www.ibm.com/products/ilog-cplex-optimization-studio/details

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