Integrated Planning and Scheduling in Transportation Infrastructure Maintenance Management

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\section{ABSTRACT}
Transportation infrastructure systems are vital to the welfare of modern society. The management of maintenance and rehabilitation activities of the transportation infrastructure systems mainly focus on two types of problems: 1) the planning problem, in which an agency with a limited budget identifies suitable maintenance treatments for the facilities and decide at which year the activities should be performed, and 2) the scheduling problem, in which the agency develops a schedule to incorporate the time at which the maintenance treatments begin and end based on the availability of daily resources. Existing studies mainly focus on the maintenance planning problem of selecting the maintenance treatment for the overall benefit of the system without considering the scheduling of daily works. However, without the proper scheduling of maintenance activities, these approaches are far less effective and could lead to overplanning of maintenance activities and shortage of resources. Motivated by these facts, this paper proposes to address the integration of planning and scheduling of transportation infrastructure maintenance activities. In this paper, a mixed integer linear programming formulation was developed to help the planning and scheduling of maintenance activities and a heuristic algorithm was proposed to solve the problem efficiently. Example networks were tested for the performance comparison between the CPLEX solver and the heuristic algorithm. The results show that the proposed model can help transportation agencies better manage their maintenance and rehabilitation activities.

Keywords: Infrastructure Management, Asset Management, Pavement Management, Maintenance Planning, Project Scheduling

\section{INTRODUCTION}
Infrastructure is the spine of the economy and a fundamental input to every economic output. It is crucial to the nation’s success and the public health and welfare. Once every four years, a Report Card for America’s infrastructure is published by the American Society of Civil Engineers (ASCE), which grades the current state of the national infrastructure categories on a scale of A through F. Ever since the year 1998, America’s infrastructure has obtained constant D averages, and failure to

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设施由于条件差而受到的损害包括车辆因额外行驶的里程而造成的损害，由于道路表面恶化而使其行驶速度降低，避免使用或交通拥挤的路段所花费的时间，以及车辆因交通拥挤而停车等待或因车辆故障而停驶所耗费的时间，以及设施由于条件差而未能得到良好维护所造成的额外成本。这种情况下，设施的可靠性也会受到影响，这意味着旅行者会根据时间来保证到达的时间（对于货物车辆来说是到达目的地的时间）。此外，交通拥挤还会增加环境和安全成本，因为更多的旅行者和车辆会处于不安全的状态，并且由于道路条件的恶化，车辆的效率会降低。因此，在这种情况下，保持交通基础设施的良好运行状态是非常重要的，因为这需要大量的资本支出和建设时间。同时，维护活动也会产生非金融性成本，而负责维护的机构会有有限的预算，因此需要确定应进行什么维护活动，以及何时进行，以确保系统的良好运行，并且在合理的成本情况下。”

3. RELATED WORKS

matical programming procedure for routine maintenance activities at the network level developed for incorporation into the existing pavement maintenance-management system of Indiana. The procedure allowed a highway agency to determine amounts of different routine maintenance activity types to be performed over a given time period under the constraints of production requirements, budget allocation, manpower, material and equipment availability, and pavement rehabilitation schedule. But the deterioration of pavement was not considered in this paper.

As discussed above, existing studies focus on either the planning of maintenance activities over certain time periods or the scheduling of daily maintenance work. But no studies has been done on integrating the planning and scheduling problem together. The consequence of this lack of research is that there may be an excessive planning of maintenance activities and not enough daily resources available to schedule the maintenance work over a given time period. Therefore, in this paper, we propose developing an integrated model that takes both planning and scheduling of maintenance activities into consideration.

4 METHODOLOGY

The formulation of the proposed model is discussed in this section. First, the planning problem and scheduling problem are discussed separately. Then, the proposed integrated model is presented. The sets, parameters, and variables mentioned in the model description are summarized in Table 1.
Table 1: Notations

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sets</td>
<td></td>
</tr>
<tr>
<td>$I$</td>
<td>Set of infrastructure facilities</td>
</tr>
<tr>
<td>$M$</td>
<td>Set of maintenance treatments</td>
</tr>
<tr>
<td>$T$</td>
<td>Set of maintenance planning periods</td>
</tr>
<tr>
<td>$K$</td>
<td>Set of resources required to implement maintenance</td>
</tr>
<tr>
<td>$H$</td>
<td>Set of scheduling horizon</td>
</tr>
<tr>
<td>Parameters</td>
<td></td>
</tr>
<tr>
<td>$B_t$</td>
<td>Budget available for maintenance in the $t$th time period, $t \in T$</td>
</tr>
<tr>
<td>$c_m$</td>
<td>The cost of applying the $m$th treatment, $m \in M$</td>
</tr>
<tr>
<td>$e_m$</td>
<td>The effectiveness of the $m$th treatment, $m \in M$</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Annual deterioration rate of facilities</td>
</tr>
<tr>
<td>$g_{mk}$</td>
<td>The $k$th resource needed for the $m$th maintenance, $k \in K, m \in M$</td>
</tr>
<tr>
<td>$p_m$</td>
<td>Duration of maintenance treatment for the $m$th facility, $m \in M$</td>
</tr>
<tr>
<td>$G_k$</td>
<td>The $k$th resource available for each work day</td>
</tr>
<tr>
<td>$m_i$</td>
<td>Selected maintenance treatment for the $i$th facility after solving the planning problem (1)-(7), $m_i \in M, i \in I$</td>
</tr>
<tr>
<td>Variables</td>
<td></td>
</tr>
<tr>
<td>$x_{it}$</td>
<td>Condition of the $i$th facility at the end of the $t$th time period, $i \in I, t \in {0} \cup T$</td>
</tr>
<tr>
<td>$s_i$</td>
<td>Initial condition of the $i$th facility</td>
</tr>
<tr>
<td>$z_{id}$</td>
<td>Binary variable indicating that the maintenance activity of the $i$th facility will start on day $d$, $i \in I, d \in H$</td>
</tr>
<tr>
<td>$y_{d}$</td>
<td>Binary variable indicating all activities are completed on day $d$, $d \in H$</td>
</tr>
<tr>
<td>$y_{itm}$</td>
<td>Binary variable indicating whether the $m$th maintenance treatment is applied to the $i$th facility in the $t$th time period, if it is, $y_{itm} = 1$, otherwise $y_{itm} = 0$. $i \in I, m \in M, t \in T$.</td>
</tr>
<tr>
<td>$u_{itmd}$</td>
<td>Binary variable and if $u_{itmd} = 1$, the $m$th maintenance treatment will be applied to the $i$th facility starting on day $d$ in year $t$. $i \in I, m \in M, t \in T, d \in H$.</td>
</tr>
</tbody>
</table>

4.1 Infrastructure Maintenance Planning Problem

A typical infrastructure maintenance planning problem (1)-(7) is to find the optimal maintenance plan so that the network-level condition is maximized. Maintenance treatments are assumed to be carried out at the end of each year. Decision-makers have to decide annually which facility should be maintained, when it should maintain and which treatment should be implemented at the facility. The maintenance works are subject to yearly budget constraints.

\[
\max \frac{1}{|I| \times |T|} \sum_{i \in I} \sum_{t \in T} x_{it} \tag{1}
\]

subject to: $x_{i0} = s_i, \forall i \in I \tag{2}$

\[
x_{it} = \rho x_{i,t-1} + \sum_{m \in M} e_m y_{itm} , \forall i \in I, \forall t \in T \tag{3}
\]
\[
\sum_{m \in M} y_{itm} \leq 1, \forall i \in I, \forall t \in T
\]  
(4)

\[
\sum_{i \in I} \sum_{m \in M} c_{m} y_{itm} \leq B_{t}, \forall t \in T
\]  
(5)

\[
0 \leq x_{it} \leq 100, \forall i \in I, \forall t \in T
\]  
(6)

\[
y_{itm} \in \{0, 1\}, \forall i \in I, \forall t \in T, \forall m \in M
\]  
(7)

The objective function (1) maximizes the average condition of all facilities over all planning horizons. \(|\cdot|\) represents the cardinality of a set. Constraint (2) assigns (known) initial conditions to each facility. Constraint (3) states that the condition of the \(i\)th facility at the end of \(t\)th year is determined by its condition at previous year multiplied by a deterioration rate and the effectiveness of the applied maintenance treatment. Constraint (4) states that each facility cannot receive more than one maintenance treatment in a single year. Constraint (5) gives a budget limitation on the annual maintenance expenditures. Constraints (6) and (7) define the decision variables \(x_{it}\) and \(y_{itm}\).

### 4.2 Resource Constrained Scheduling Problem

When the maintenance activities are determined for each facility through (1)-(7), a resource-constrained project scheduling problem (8)-(13) can be used to find a schedule of minimal duration by assigning a start time to each activity and also taking the resource availabilities into consideration.

\[
\min \sum_{d \in H} d y_{id}
\]  
(8)

subject to:

\[
\sum_{d \in H} d y_{id} \geq \sum_{d \in H} d z_{id} + p_{i}, \forall i \in I
\]  
(9)

\[
\sum_{d \in H} z_{id} = 1, \forall i \in I
\]  
(10)

\[
\sum_{i \in I} g_{m,k} \sum_{\tau = d - p_{i} + 1}^{d} z_{i\tau} \leq G_{k}, \forall k \in K, \forall d \in H
\]  
(11)

\[
y_{id} \in \{0, 1\}, \forall d \in H
\]  
(12)

\[
z_{id} \in \{0, 1\}, i \in I, d \in H
\]  
(13)

The objective function (8) minimizes the number of days to complete all activities over the scheduling horizon. Constraint (9) defines the end day of all activity. Constraint (10) ensures each activity to be scheduled has only one start day. Constraint (11) checks if each resource is available for the duration of the activity.
4.3 Integrated Maintenance and Scheduling Problem

In the proposed integrated model (14)-(23), it is assumed that at the end of each year maintenance treatments are performed. It is the responsibility of the decision makers to decide annually based on the initial condition of the facility, the available resources and budget the facility to be maintained, the maintenance treatment to be implemented and the time at which these should be done on the facility. The objective function (14) of the proposed model is to maximize the average condition of the infrastructure systems over the planning horizon.

\[
\max \frac{1}{|I| \times |T|} \sum_{i \in I} \sum_{t \in T} x_{it} \quad (14)
\]

Equations (15)-(16) show that the condition of the \(i\)th facility at the \(t\)th year is determined by the initial condition \(x_{i0}\), deterioration rate \(\rho\) and maintenance effectiveness \(e_m\) over the years.

\[
x_{i0} = s_i, \forall i \in I
\]

\[
x_{it} = \rho x_{i,t-1} + \sum_{m \in M} e_m y_{itm}, \forall i \in I, \forall t \in T \quad (16)
\]

Equation (17) limits the number of funded treatments per year for a specific facility.

\[
\sum_{m \in M} y_{itm} \leq 1, \forall i \in I, t \in T \quad (17)
\]

Equation (18) is the budget constraint, which restricts the maintenance expenditure to be below a given budget, where \(c_m\) is the cost for the \(m\)th treatment and \(B_t\) is the available budget in year \(t\).

\[
\sum_{i \in I} \sum_{m \in M} c_m y_{itm} \leq B_t, \forall t \in T \quad (18)
\]

Equation (19) ensures that the variable \(u_{itm}\) equals to 0 if no maintenance treatment is selected for the \(i\)th facility in year \(t\). It also enforces that there is only one starting day if a maintenance treatment is selected.

\[
\sum_{d \in H} u_{itm} = y_{itm}, \forall i \in I, t \in T, m \in M \quad (19)
\]

Constraint (20) considers the available daily resources \(G_k\), and checks if there is sufficient resources available for the duration of each planned maintenance activity.

\[
\sum_{i \in I} \sum_{m \in M} g_{mk} \sum_{\tau=d-p_m+1}^{d} u_{itm\tau} \leq G_k, \forall d \in H, k \in K, t \in T \quad (20)
\]

Constraint (21) restricts the condition of the facility between 0 to 100.

\[
0 \leq x_{it} \leq 100, \forall i \in I, t \in T \quad (21)
\]
Constraint (22) defines decision variables $y_{itm}$ which is a binary variable indicating whether the $m$th maintenance treatment is applied to the $i$th facility in the $t$th time period.

$$y_{itm} \in \{0, 1\}, \forall i \in I, t \in T, m \in M$$ (22)

Finally, constraint (23) defines decision variable $u_{itmd}$ which is a binary variable indicating the day $d$ of when the maintenance activity will begin, of the $i$th facility receiving the $m$th treatment at year $t$.

$$u_{itmd} \in \{0, 1\}, \forall i \in I, t \in T, m \in M, d \in H$$ (23)

### 4.4 Heuristic Algorithm

One limitation of the above model formulation is that the size of the problem grows exponentially and therefore incurs prohibitive computational time when the number of facilities increases. To circumvent this problem, we developed a three-phase heuristic algorithm to solve the proposed model.

In the first phase, the maintenance treatment with the highest cost-benefit ratio is selected for each facility so that it will stay in good condition for the upcoming year. The selection is determined by considering the deterioration of the facility and the effectiveness of the maintenance treatment.

In the second phase, the budget is allocated to the facilities having highest cost benefit ratio. The remaining budget is allocated to the remaining facilities in the same manner. This process is repeated until the budget is exhausted. The facilities having the worst condition are preferred in cases where multiple facilities have the same maintenance level of need.

In the third phase, the selected activities is scheduled. The algorithm checks each day of the planning horizon starting from the first day. If the resources are available for the whole duration of the maintenance activity, then the activity begins on that day. Otherwise, the algorithm will search the next day and so on. These three phases will be repeated for the planning horizon.

### 5 CASE STUDY

In this case study, two road network examples are presented to illustrate the proposed integrated planning and scheduling maintenance problem and the developed algorithm. One is a small size problem and the other is a large size problem. While the exact solution of the first example is obtained using the CPLEX solver, the second example is solved using heuristic algorithm.

#### 5.1 Example 1

For illustration purposes, this example maintenance planning problem has 50 pavement sections. The planning horizon is assumed to be 4 years. During the planning horizon, all road sections are eligible for maintenance treatments, which are assumed to be applied at the end of each year. The annual budget is set at $1,000,000. The condition score (CS) is selected as the pavement condition indicator. Condition score represents the pavement’s overall condition in terms of both distress and ride quality (serviceability index values). It ranges from 1 (the worst condition) to 100 (the best condition) [22].
For demonstration purposes, the deterioration rate $\rho$ is set at 0.95. The selection of the deterioration rate is taken from previous studies (e.g., [9]). The daily resource available is considered to be 30 manpower and 20 machinery. As shown in Table 2, five maintenance treatments options were used in this case study. The maintenance treatments cost $c_m$, effectiveness $e_m$, the typical maintenance treatments, daily resource and duration were prepared on the basis of information from previous studies [7,9,21,23,24,25].

Table 2: Cost and Effectiveness of Maintenance Treatments

<table>
<thead>
<tr>
<th>Notations in proposed model ($m$)</th>
<th>Maintenance treatment</th>
<th>Maintenance treatment unit cost ($1000$)</th>
<th>Average condition score increase</th>
<th>Daily resource required (manpower, machinery)</th>
<th>Duration (Days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Needs Nothing (NN)</td>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>Preventive maintenance (PM) includes Seal Coats (Chip Seals), Thin Overlays $&lt;$ 2&quot;, and Micro-Surfacing</td>
<td>6.1</td>
<td>3</td>
<td>(6,2)</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>Light rehabilitation (LRhb) includes $2'' \leq$ Overlays $&lt;$ 3&quot;, Widening Pavement and Seal Coat, Base Repairs and Seal coat, Mill, Seal, and Thin Overlay</td>
<td>21</td>
<td>15</td>
<td>(9,3)</td>
<td>7</td>
</tr>
<tr>
<td>3</td>
<td>Medium rehabilitation (MRhb) includes $3'' \leq$ Overlays $&lt;$ 5&quot;, Mill and Inlay (Mill and Fill), Mill, Stabilize Base, and Seal, Level Up and Overlay, Base Repairs and Overlay</td>
<td>46</td>
<td>25</td>
<td>(9,5)</td>
<td>21</td>
</tr>
<tr>
<td>4</td>
<td>Heavy rehabilitation (HRhb) includes Full Pavement Reconstruction, Bomag, Add Base, and Overlay or Seal</td>
<td>110</td>
<td>40</td>
<td>(11,7)</td>
<td>90</td>
</tr>
</tbody>
</table>

The first year optimal solution is shown in Figure 1. The planned maintenance activities are scheduled over the duration of a calendar year with 261 work days. The schedule shows the selected maintenance treatment of different sections, the start day of each treatment, and the duration of each treatment. For example, section 36 will be maintained with medium rehabilitation, which takes 21 days to finish. The maintenance project will start on day 132 and end on day 153.
To check whether the resources are being utilised efficiently, the resource consumption is calculated in two scenarios: 1). the planning problem and the scheduling problem of maintenance activities are solved separately, and 2). the proposed integrated model is solved.

Figure 2 shows the first scenario. As can be seen in Figure 2, to complete the maintenance activities on the selected facilities, the daily resources required are more than double the available daily resources. Since only planning is considered, the amount of maintenance activities selected are higher and the consumption of resource 1 and 2 is higher than the available daily resources.

When the integrated planning and scheduling problem is solved, the resource consumption is shown in Figure 3. As can be seen in Figure 3, the maintenance activities of the selected facilities are scheduled in an optimal manner and the daily resource consumption of resource 1 and 2 are within the available daily resources since both planning and scheduling are considered.
5.2 Example 2

In Example 2, the integrated maintenance planning and scheduling problem was solved for a road network with 1,000 pavement sections using the heuristic algorithm. The purpose of this example is to test the computational efficiency of the proposed heuristic algorithm when it is applied to practical-sized problems. The choices of maintenance treatments and deterioration rate are assumed the same as in example 1.

Figure 4 shows the schedule of the sections as per the maintenance treatment selected. Out of the 1,000 pavement sections, 87 are scheduled maintenance in the first year because of limited budget and resources. This schedule shows the type of maintenance treatment selected for the pavement section, the start day of the treatment and the day the duration of the maintenance treatment. Further experiment shows that the heuristic algorithm is able to solve the integrated planning and scheduling problem with up to 10,000 sections in 2 minutes and 23 seconds.

Figure 3: Consumption of resources when only planning and scheduling is considered.

Figure 4: Maintenance Activity Schedule of First Year (Red = Preventive maintenance, Blue = Light rehabilitation, Green = Medium rehabilitation, Yellow = Heavy rehabilitation)
In this paper, the authors developed an integer linear programming model that integrates both maintenance planning and scheduling problems for transportation infrastructure maintenance management. In the developed model, the authors take into consideration of the maintenance type, cost and effectiveness. The daily resources (both manpower and equipment) available is also included in the model for the scheduling of maintenance activities.

The authors also developed a three-phase heuristic algorithm to solve the proposed model, that produces near-optimal solutions with computational time being reduced substantially as compared to the CPLEX solver. Thanks to this substantial time saving, computationally efficient solutions to more complicated network-level problems can be formulated by using heuristic as a building block.

Two road network examples are presented to illustrate the proposed integrated planning and scheduling maintenance problem and the developed algorithm. The case study results show that the developed heuristic algorithm give good results compared with the results from the CPLEX solver. The two examples also illustrate the daily consumption of resources for two scenarios. As a result, the resource consumption when considering both the planning and scheduling together provides a more feasible and optimal solution.

In this research, the developed model has only considered an in-house approach, in which the infrastructure management agency uses the resources and equipment that are available within the agency. For future research, the model can also include the scenarios where the maintenance work can be outsourced to contractors if the planned work cannot be completed by internal resources.

References


