Considering Deterioration Propagation in Civil Infrastructure Maintenance Planning

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ABSTRACT

Civil infrastructure system maintenance planning is to determine which facility should be repaired, when and how maintenance should be carried out, and what treatment should be used under budget and other resource constraints. In the existing literature, various simulation and optimization models have been developed to help select the optimal maintenance plan. However, the developed models overlooked the deterioration propagation between adjacent connected facilities of the network infrastructure system. For instance, a facility receiving zero maintenance or having a failure of maintenance treatment affects not only the condition of itself, but also the deterioration rate of its neighboring facilities. This raises the call for taking the deterioration propagation into consideration when developing optimization models and capture to which extent it can affect the optimal maintenance plan. Therefore, in this paper, an infrastructure maintenance planning model considering the deterioration propagation between facilities is formulated as a mixed integer linear programming problem. A heuristic algorithm was proposed to solve the problem efficiently. Example networks were tested for the performance comparison between CPLEX and the heuristic algorithm. The results of the optimization models with and without the deterioration propagation effect were compared and discussed.

keywords: Deterioration Propagation, Infrastructure Interdependence, Maintenance Planning, Infrastructure Management, Optimization

1 INTRODUCTION

Civil infrastructure systems (e.g., roads, bridges, water supply, and wastewater) are exposed to aging effects and eventually subject to failure if no maintenance intervention is carried out. To prevent/delay failures, maintenance treatments need to be applied periodically. In order to optimize the allocation of resources for maintenance of the facilities, maintenance planning is needed. The primary objective of maintenance planning is to help decision makers schedule maintenance actions and determine which facility need to be maintained, when maintenance should be carried out, and which treatments should be used. As civil infrastructure systems are spatially distributed assets covering large regions, they are specially characterized by the interdependence and interaction within and between different systems. Researchers have developed maintenance planning models addressing different relationships between facilities/systems from functional, economic, and other perspectives. For example, Durango and Sarutipand [1] developed a quadratic programming formulation for designing repair and maintenance policies of multi-facility transportation infrastructure systems. In this model, the authors considered the assumption that the use of one infrastructure facility affects other infrastructure facilities. Moreover, this model also took into account the economic dependencies between facilities in different systems. Chu and Chen [2] developed a bi-level programming model for transportation infrastructure maintenance plan by taking the users' responses to maintenance actions into consideration. Zou and Madanat [3] presented an approach to address pavement management decision problems at airports with multiple runways by considering functional dependency between runways. Bernhardt and McNeil [4] stated that pavements are interconnected through geography, which implied the economies of scale in contracting long stretches of pavement for rehabilitation and the dis-economies of scale in terms of the disruption to users. Gao and Zhang [5] also pointed out that road sections selected for maintenance by traditional optimization approach are usually distributed spatially across the network. The authors suggested that, to take advantage of economies of scale, adjacent pavement sections with similar maintenance needs should be maintained within a single project.

Several studies have also been conducted on maintenance planning models addressing cracking propagation in pavement network. For example, Majidzadeh et al. [6] made an early attempt to study crack propagation using fracture testing. Jacobs et al. [7] employed ParisâĂŹ law to analyze cracking in asphalt concrete and to obtain more insight into the crack propagation and resistance of asphalt mixes. Song et al. [8] also presented simulation of crack propagation in asphalt concrete using an intrinsic cohesive zone model. The authors introduced a powerful numerical scheme using the cohesive zone model (CZM) concept to investigate the fracture behavior of asphalt concrete and to simulate crack initiation and propagation of cracks.

Despite of the studies discussed above, the propagation of deterioration from one facility to the adjacent facilities have not been considered in maintenance planning of infrastructure management. It has been found by previous studies that infrastructure deterioration usually propagates to its surrounding facilities. In other words, a facility receiving zero maintenance or having a failure of maintenance treatment affects not only the condition of itself, but also the deterioration rate of its neighboring facilities. For example, pavement cracks usually begin as hairline or very narrow cracks. When water enters the underlying layers of the pavement through the cracks, it may cause changes such as pumping, swelling and migration of finer materials to widen the crack. If not properly sealed and maintained, secondary or multiple cracks will develop parallel to the initial crack. Moreover, the crack edges can further deteriorate by raveling and eroding the adjacent pavement facilities [9].

Another example, when stress corrosion cracks occur in pipelines, it increases the probability that a pipe break can occur that creates a whipping pipe with the potential to damage adjacent piping and its attached wall [10]. Motivated by these facts, we developed a new mixed integer linear programming model to address this problem. The model developed finds the optimal maintenance plan that takes the propagation of deterioration into consideration.

2 Related Work

There are two types of civil infrastructure systems maintenance planning problems depending on the number of facilities under consideration. The first one is the project-level maintenance management problem, in which the maintenance plan of only one or a few facilities is considered. The other is the network-level problem, where decision-makers determine which facility should be repaired, when and how repairs should be carried out, and what treatment should be used for large-scale infrastructure networks.

In existing literature, various optimization models were developed for the project-level maintenance management problem. Among them, dynamic programming [11, 12, 13], optimal control theory [14, 15, 16], mixed nonlinear/linear integer programming [17, 18, 19], reliability based maintenance/replacement models [20, 21] are the most popular ones and have been extensively used for infrastructure maintenance optimization. Due to page limitation, only a few works are briefly explained here. For example, Ouyang [14] developed an analytical solution for project-level pavement maintenance planning problem assuming that treatment is implemented at discrete time periods and condition indicator is continuous. Boyles et al. [12] used dynamic programming to solve infrastructure maintenance and repair policies with nonlinear agency cost. Frangopol et al. [20] developed a reliability-based life-cycle model for bridge infrastructure.

Network-level infrastructure maintenance planning problems are usually formulated as linear programming (LP) [22, 23, 24] or mixed integer linear/nonlinear programming (MIP) problems [25, 26, 27]. In these models, a set of time points at which maintenance treatments might be applied is predefined. The solutions of such models are to determine which maintenance treatment should be applied at which specific time point.

MIP models require significant computational effort to solve, especially when dealing with large-scale infrastructure systems. The complexity of MIP models mentioned above increases exponentially as the size of the problem increases. Infrastructure agencies typically face network-level maintenance management problems with thousands or even more management units within the system. For this reason, some researchers looked into meta-heuristic models [28, 29, 30] and decomposition techniques [31, 32] to handle large-scale maintenance planning problems. For example, Karabakal et al. [31] and Dahl et al. [32] applied the Lagrangian relaxation technique to decompose the network-level MIP problem into individual sub-problems. Then, each sub-problem was solved by the shortest path algorithm. By relaxing the budget constraint, the relaxed original problem can be partitioned into many smaller sub-problems. The solution to the original problem can be approximated by iteratively reducing the gap between the upper and lower bounds, where the upper bound is determined by solving the sub-problems, and the lower bound is estimated by constructing a feasible solution based on the subproblem solutions.

3 Methodology

In this research, we proposed a new mixed integer programming formulation to analyze the deterioration propagation in the optimization of maintenance planning. The formulation of the proposed model is discussed in this section. The sets, parameters, and variables mentioned in the model description are summarized in Table 1.

Table 1: Notations

Term	Definition
Sets	
N	Set of infrastructure facilities, $N = \{1, 2 \ldots, n\}$
M	Set of maintenance treatments, $M = \{1, 2, ..., k\}$
T	Set of maintenance planning periods, $T = \{1, 2, \ldots, v\}$
Parameters	
B_t	Budget available for maintenance in the tth time period
c_m	The cost of applying the mth treatment
e_m	The effectiveness of the mth treatment
g	The threshold of good condition state. When $x_{it} \geq g$, the ith facility is considered to be in good condition state in the tth time period.
γ	Deterioration propagation rate
h	Minimum percentage of the infrastructure facilities that are required to be in good condition state
ρ	Deterioration rate of facilities
s_i	Condition of the ith facility at the beginning of the planning horizon
R	A big number
Variables	
x_{it}	Condition of the ith facility in the tth time period
$x_{it1}, x_{it2}, x_{it3}$	Variables representing x_{it} in different domains
$w_{it1}, w_{it2}, w_{it3}$	Special ordered set (SOS) binary variables, which are used to restrict the condition of facility to be between 0 and 100
y_{itm}	Binary variable indicating whether the mth maintenance treatment is applied to the ith facility in the tth time period, if it is, $y_{itm} = 1$, otherwise $y_{itm} = 0$
z_{it}	Binary variables indicating if the condition of the ith facility is in good condition state in the tth time period

3.1 Formulations

In this formulation, 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. In this model, the deterioration propagation relationship of adjacent facilities is also considered. We assume that the layout of the infrastructure network is set up as shown in Figure 1. In this layout, each facility (except the ones at both ends) has two neighboring facilities.

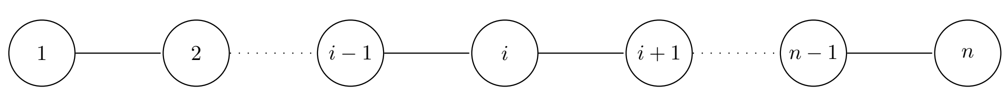

Figure 1: Example layout of an infrastructure network.

We assume that the condition indicator of all facilities are between 0 and 100 with 0 representing the worst and 100 representing the best. To restrict the condition of a facility to be within 0 to 100, special ordered sets of type 1 (SOS1) variables are used. The idea of constraints (1)-(7) is to ensure that even if the calculated condition of facility is above 100 or below 0 after some calculations, only the part between 0 and 100 will be used for further evaluation. As shown in constraint (2), binary variables w_{it1},w_{it2} and w_{it3} are part of a special ordered set, which means that exactly one of them can be one and the others are zero. Constraint (3) shows that if the condition of the facility is lower than zero, then w_{it1} will be equal to 1. If the calculated condition of the facility is between 0 to 100, w_{it2} will be 1 and x_{it2} will represent the condition of the facility as shown in constraint (4). Constraint (5) and (6) ensures that even if the calculated condition of the facility is greater than 100, only 100 will be used for further calculation.

$$x_{it} = x_{it1} + x_{it2} + x_{it3}, \forall i \in N, \forall t \in T \tag{1}$$

$$w_{it1} + w_{it2} + w_{it3} = 1, \forall i \in N, \forall t \in T \tag{2}$$

$$-Rw_{it1} \leq x_{it1} \leq 0, \forall i \in N, \forall t \in T \tag{3}$$

$$0 \leq x_{it2} \leq 100w_{it2}, \forall i \in N, \forall t \in T \tag{4}$$

$$x_{it3} \geq 100w_{it3}, \forall i \in N, \forall t \in T \tag{5}$$

$$x_{it3} \leq Rw_{it3}, \forall i \in N, \forall t \in T \tag{6}$$

$$w_{it1}, w_{it2}, w_{it3} \in \{0, 1\}, \forall i \in N, \forall t \in T \tag{7}$$

The objective function (8) of the proposed model is to maximize the average condition of the infrastructure systems over the planning horizon. As discussed above, the use of $x_{it2} + 100w_{it3}$ in the objective function is to ensure that only the $[0, 100]$ part of the condition index are counted in evaluating the performance.

$$\max \frac{1}{nv} \sum_{i \in N} \sum_{t \in T} (x_{it2} + 100w_{it3}) \tag{8}$$

At the beginning of the planning horizon, the conditions of facilities are already known to the decision makers. Constraint (9) assigns initial condition to each facility in the system.

$$x_{i0} = s_i, \forall i \in N \tag{9}$$

In this model, we assume that the condition of an facility in a given time period is determined by its previous year's condition, deterioration rate, effectiveness of the maintenance treatment applied during this time period, and the effect from neighboring facilities. As shown in Figure 1, all facilities of the infrastructure network have two adjacent facilities except the first and the last facility. Constraint (10) represents the deterioration process for the 1st facility in the first year. The propagation of deterioration from its neighboring facility is modeled as $\gamma (100 - x_{2,0})$, where γ is propagation rate and $x_{2,0}$ is the initial condition of the second facility. By modeling in this way, the deterioration propagation is assumed to be determined by the condition of the adjacent facilities. The worse a facility's condition is, the greater the negative impact it will pass on to its neighbors. Constraint (11) represents the first year's deterioration process of the 2nd to the $n - 1$th facilities, where all facilities have two neighbors. Constraint (12) shows the deterioration process for the last facility of the network in the first year. Constraints (13), (14) and (15) represent the deterioration process of facilities from the second year to the end of planning horizon. SOS1 variables x_{it2} and w_{it3} are introduced to ensure that facility conditions are within 0 to 100 when they are used to calculate next year's conditions.

$$x_{11} = \rho x_{10} - \gamma (100 - x_{2,0}) + \sum_{m \in M} e_m y_{11m} \tag{10}$$

$$x_{i1} = \rho x_{i0} - \gamma\left(100 - x_{i-1,0}\right) - \gamma\left(100 - x_{i+1,0}\right) + \sum_{m\in M} e_m y_{itm}, \forall i \in N\backslash\{1,n\} \tag{11}$$

$$x_{n1} = \rho x_{n,0} - \gamma\left(100 - x_{n-1,0}\right) + \sum_{m\in M} e_m y_{n1m} \tag{12}$$

$$x_{1t} = \rho\left(x_{1,t-1,2} + 100w_{1,t-1,3}\right) - 2\gamma\left(100 - x_{2,t-1,2} - 100w_{2,t-1,3}\right) + \sum_{m\in M} e_m y_{1tm}, \forall t \in T\backslash\{1\} \tag{13}$$

$$\begin{aligned} x_{it} =& \rho\left(x_{i,t-1,2} + 100w_{i,t-1,3}\right) - \gamma\left(100 - x_{i-1,t-1,2} - 100w_{i-1,t-1,3}\right) \\ &- \gamma\left(100 - x_{i+1,t-1,2} - 100w_{i+1,t-1,3}\right) + \sum_{m\in M} e_m y_{itm}, \forall i \in N\backslash\{1,n\}, \forall t \in T\backslash\{1\} \end{aligned} \tag{14}$$

$$x_{nt} = \rho\left(x_{i,t-1,2} + 100w_{n,t-1,3}\right) - 2\gamma\left(100 - x_{n-1,t-1,2} - 100w_{n-1,t-1,3}\right) + \sum_{m\in m} e_m y_{ntm}, \forall \in T\backslash\{1\} \tag{15}$$

Constraint (16) limits the number of funded treatments per year for a specific facility. Constraint (17) is the budget constraint, which restricts the maintenance expenditure to be below a given budget, where c_m is the cost for the mth treatment and B_t is the available budget in year t.

$$\sum_{m\in M} y_{itm} = 1, \forall i \in N, t \in T \tag{16}$$

$$\sum_{i\in N}\sum_{m\in M} c_m y_{itm} \leq B_t, \forall t \in T \tag{17}$$

Some infrastructure agencies often define a facility whose condition is in a certain range to be in good condition state. For example, the Texas Department of Transportation requires 90% of the pavement sections in the network should have 70 or higher condition scores [33]. To incorporate these requirements into the model, variable z_{it} is used to indicate whether a facility is in good condition state. In constraint (18), g is the threshold of good condition state. Constraint (19) states at least h percentage of facilities should be in good condition state.

$$x_{it} \geq g z_{it}, \forall i \in N, \forall t \in T \tag{18}$$

$$\frac{\sum_{i\in N}\sum_{t\in T} z_{it}}{nv} \geq h \tag{19}$$

Finally, constraint (20) and (21) define the decision variables y_{itm} and z_{it}. y_{itm} is a binary variable indicating whether to implement the m'th maintenance action for the i'th facility in the tth time period. z_{it} is a binary variable indicating whether the condition of the ith facility is greater than 70.

$$y_{itm} \in \{0,1\}, \forall i \in N, \forall t \in T, \forall m \in M \tag{20}$$

$$z_{it} \in \{0,1\}, \forall i \in N, \forall t \in T \tag{21}$$

3.2 Heuristic Approach

One drawback 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 heuristic algorithm to solve the proposed model. The algorithm is described in the following steps.

1. Initialize number of facilities in the network (N), maintenance treatments (e_m, c_m), number of year (T), deterioration rate (ρ), deterioration propagation rate (γ), minimum percentage requirement (h), good condition state (g)

2. For $t \in T$, follow the steps below.

   (a) Make the set S empty. For each facility $i \in N$, its end-of-year condition x_{it} is calculated using its previous year's condition $x_{i,t-1}$, deterioration rate ρ, and deterioration propagation γ .

      i. If $x_{it} \geq g$, then no maintenance treatment is selected.

      ii. Otherwise, select the cheapest maintenance treatment m such that $x_{it} + e_m \geq g$ and assign i to S.

   (b) Rank all facilities in S by their maintenance costs c_m from low to high.

      i. If two facilities have the same maintenance cost, then the facility with lower condition will be prioritized.

   (c) Allocate year t's budget to the sorted S according to their ranking.

      i. If the budget runs out before the percentage constraint is satisfied, there is no feasible solution.

      ii. If the percentage constraint is satisfied before budget runs out, proceed to next step.

   (d) The facilities that have not received maintenance treatment are ranked by their previous year's condition from low to high.

   (e) Allocate year t's remaining budget to the ranked facilities until budget runs out.

4 CASE STUDY

In this case study, two examples are presented to illustrate the proposed infrastructure network maintenance problem and the developed algorithm. One is a small size problem and the other is a large size problem. First example is solved through exact solution (ILOG CPLEX Solver). We found that as the problem size grows, the model size quickly expands to an extent that the ILOG CPLEX Solver can hardly manage. The heuristic algorithm is tested on the second example.

4.1 Example 1

For illustration purposes, this example maintenance planning problem has 30 pavement sections. This example is solved using CPLEX solver. The purpose of this example is to demonstrate the optimal maintenance plan and section conditions after maintenance actions. The planning horizon is assumed to be 3 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 $500,000. Data from the Texas Pavement Management Information System (PMIS) was used for this example. The PMIS is the Texas Department of Transportation (TxDOT) version of Pavement Management System, which is a set of computer programs for storing, retrieving, analyzing, and reporting information to assist decision makers (highway managers in Texas DOT) to make cost-effective decisions regarding the maintenance and rehabilitation of pavements [34]. The pavement 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)[35]. The initial condition of each section is selected from highway FM0004K in year 2000 and the reference markers of these sections range from 336 to 350.

For demonstration purposes, the deterioration rate ρ is set at 0.95 and the deterioration propagation rate γ is set as 0.04. The selection of the deterioration rate is taken from previous studies [36, 37]. In Table 2, five maintenance treatments options were used in this case study. The five predefined maintenance treatments y_{itm} with cost c_m and effectiveness e_m were prepared on the basis of information from Wang et al. [25].

Table 2: Cost and Effectiveness of Maintenance Treatments

Notations in proposed model	Maintenance treatment	Maintenance treatment unit cost ($1000)	Average condition score increase
1	Needs Nothing (NN)	0	0
2	Preventive maintenance (PM)	6.1	3
3	Light rehabilitation (LRhb)	21	15
4	Medium rehabilitation (MRhb)	46	25
5	Heavy rehabilitation (HRhb)	110	40

The results of the optimal maintenance treatment decisions are presented in Table 3, which represents the condition and maintenance choices for both scenarios considering the deterioration propagation and without considering the deterioration propagation. The value of h is assumed to be 0.9, which means that 90 percent of sections should be in good condition state (condition more than $g = 70$). Table 3 indicates that the condition of the pavement deteriorates faster with the deterioration propagation rate. In other words, consideration of the deterioration propagation rate in the deterioration process affects the performance of the model.

Table 3: Results of Maintenance Plan for 30 sections ($h = 0.9$, $g = 70$,$\rho = 0.95$, B=\$500k)

Section No.	Deterioration Propagation Rate	Initial Condition	Year 1 Maintenance Choice	Year 1 Condition	Year 2 Maintenance Choice	Year 2 Condition	Year 3 Maintenance Choice	Year 3 Condition
1	γ= 0	74	1	70	3	82	3	93
	γ= 0.04		1	68	1	63	3	74
2	γ= 0	74	3	85	3	96	1	91
	γ= 0.04		3	83	3	89	1	82
3	γ= 0	63	3	75	3	86	3	97
	γ= 0.04		3	73	3	80	3	89
4	γ= 0	83	3	94	1	89	3	100
	γ= 0.04		1	77	3	84	1	79
5	γ= 0	99	1	94	1	89	3	100
	γ= 0.04		1	93	1	84	1	79
6	γ= 0	100	1	95	1	90	1	86
	γ= 0.04		1	94	1	84	1	79
7	γ= 0	77	3	88	1	84	1	80
	γ= 0.04		1	72	3	79	3	88
8	γ= 0	71	3	82	1	78	3	89
	γ= 0.04		3	80	1	70	3	79
9	γ= 0	59	3	71	3	82	3	93
	γ= 0.04		1	53	3	60	3	70
10	γ= 0	61	3	73	3	84	3	95
	γ= 0.04		3	71	3	78	1	72
11	γ= 0	88	1	84	1	79	1	75
	γ= 0.04		3	96	1	86	1	80
12	γ= 0	77	3	88	3	99	1	94
	γ= 0.04		1	71	3	78	1	72
13	γ= 0	63	3	75	3	86	3	97
	γ= 0.04		3	73	3	79	3	88
14	γ= 0	72	3	83	1	79	3	90
	γ= 0.04		3	81	1	72	3	82
15	γ= 0	73	1	69	3	81	3	92
	γ= 0.04		3	82	3	88	3	97
16	γ= 0	73	3	84	3	95	1	90
	γ= 0.04		3	82	3	87	3	97
17	γ= 0	62	3	74	3	85	3	96
	γ= 0.04		3	70	3	76	3	85
18	γ= 0	40	3	53	3	65	3	77
	γ= 0.04		3	51	3	60	3	70
19	γ= 0	94	1	89	1	85	1	81
	γ= 0.04		3	100	1	91	1	84
20	γ= 0	100	1	95	1	90	1	86
	γ= 0.04		1	94	1	89	1	83
21	γ= 0	77	1	73	3	84	1	80
	γ= 0.04		3	88	1	80	3	90
22	γ= 0	100	1	95	1	90	1	86
	γ= 0.04		1	94	3	100	1	93
23	γ= 0	97	1	92	1	88	1	83
	γ= 0.04		1	92	1	83	1	79
24	γ= 0	90	1	86	3	96	1	91
	γ= 0.04		3	100	1	91	1	85
25	γ= 0	94	1	89	1	85	3	96
	γ= 0.04		1	89	1	84	1	79
26	γ= 0	100	1	95	1	90	1	86
	γ= 0.04		1	95	1	85	1	80
27	γ= 0	94	1	89	1	85	1	81
	γ= 0.04		1	89	1	81	1	75
28	γ= 0	100	1	95	1	90	1	86
	γ= 0.04		1	94	1	85	3	95
29	γ= 0	90	1	86	1	81	1	77
	γ= 0.04		1	84	3	89	1	82
30	γ= 0	65	3	77	3	88	3	99
	γ= 0.04		1	61	1	50	3	62

Figure 2 demonstrates the relationship between the network average condition and the annual budget assuming different values (0, 0.02, and 0.04) of deterioration propagation rate. Difference within curves is significant when the budget value is low and it gradually reduces to zero when the budget increases. It can be seen that the curves remain almost flat when the budget constraint is above $250,000, which is approximately the threshold where different values of γ don't make difference. For an annual budget above $250,000, the effect of the deterioration propagation rate on the value of the total objective function is very small. This result indicate that, for low budget level, an increase in the deterioration propagation rate results in higher network average condition.

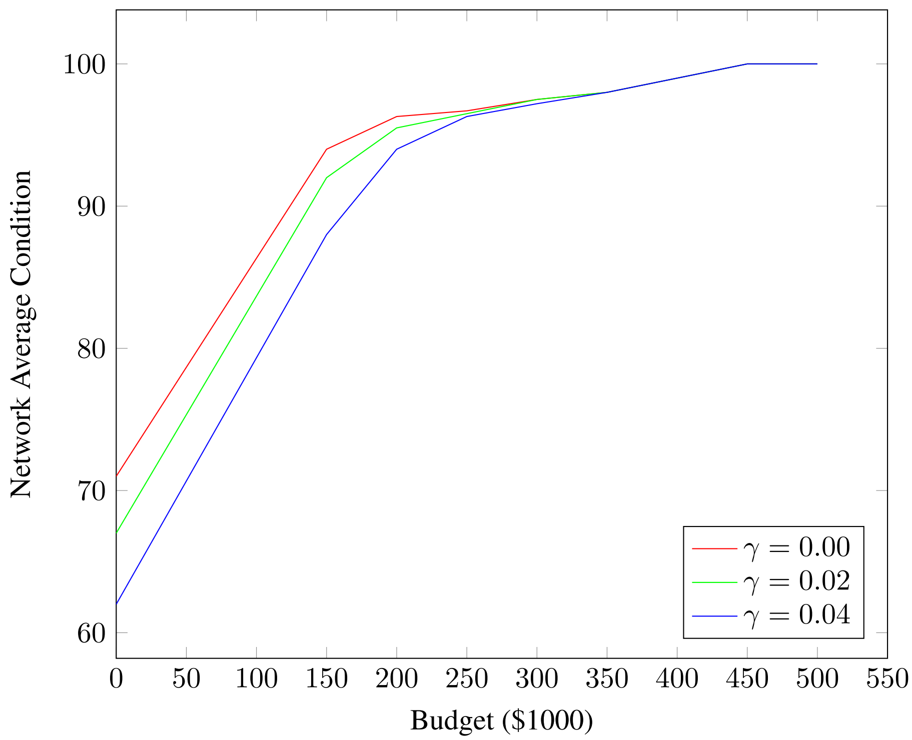

Figure 2: Budget vs. network average condition for different deterioration propagation rates ($N = 30$, $T = 4$, $g = 70$, $h = 0$, $\rho = 0.95$).

Figure 3 illustrates the relationship between the budget and the network average condition with different minimum requirements on the percentage of network in good condition state. The value of h varies between 0 and 0.5. When h is 0, Figure 3 shows that, regardless of the budget, feasible solutions can always be obtained. However, the values of h can not be satisfied at every budget value. For example, the green line shows the optimal solution with the constraint that 20 percent (h=0. 2) of the total road network should be in good condition state. As can be seen in Figure 3, with $h = 0.2$ the model has no feasible solution when budget is below $150,000. This leads to the obvious conclusion that more budget is needed to meet a higher requirement of h. Figure 3 also shows that when budget is large enough, the value of h does not make a difference in the optimal solution.

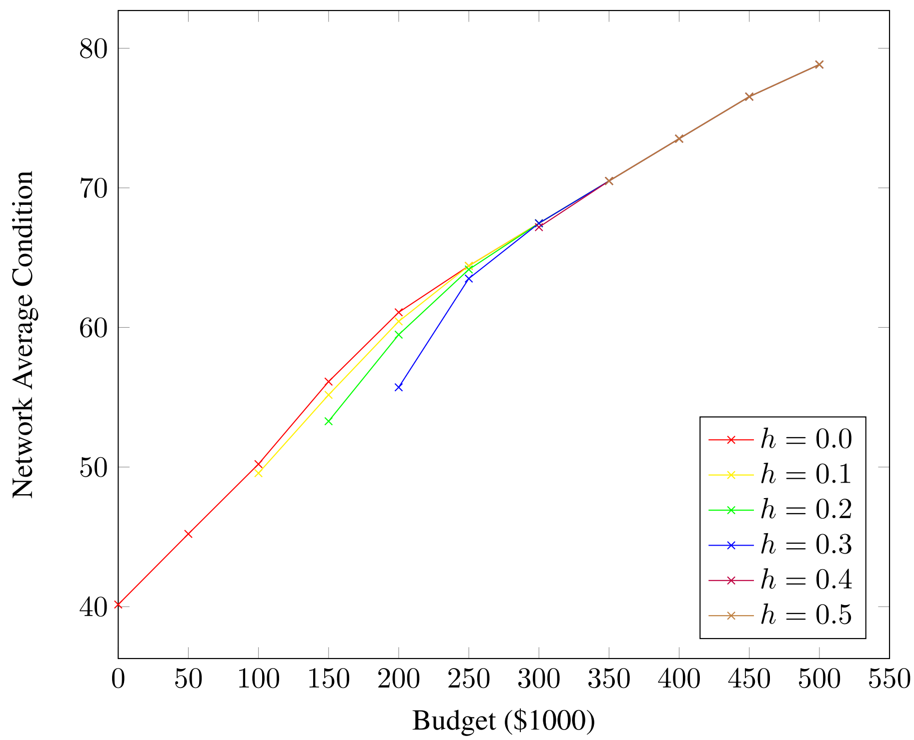

Figure 3: Budget vs. network average condition ($N = 30$, $T = 3$, $B = \$500,000$, $\rho = 0.95$, $\gamma = 0.04$, $g = 70$).

Figure 4 shows the comparison between the optimal solutions obtained from two scenarios. While the first scenario (the blue line) takes the deterioration propagation rate γ into consideration when planning maintenance treatments, the second scenario (the green line) treats $\gamma = 0$ no matter what the real propagation rate is. The number of pavement sections, planning period, budget and the minimum percentage constraints are kept constant for both scenarios. It can be seen in Figure 4 that as the value of the deterioration propagation rate increases, the difference between both scenarios also increases. This result concludes that taking the deterioration propagation into consideration gives rise to better maintenance plan when the propagation rate is greater than zero.

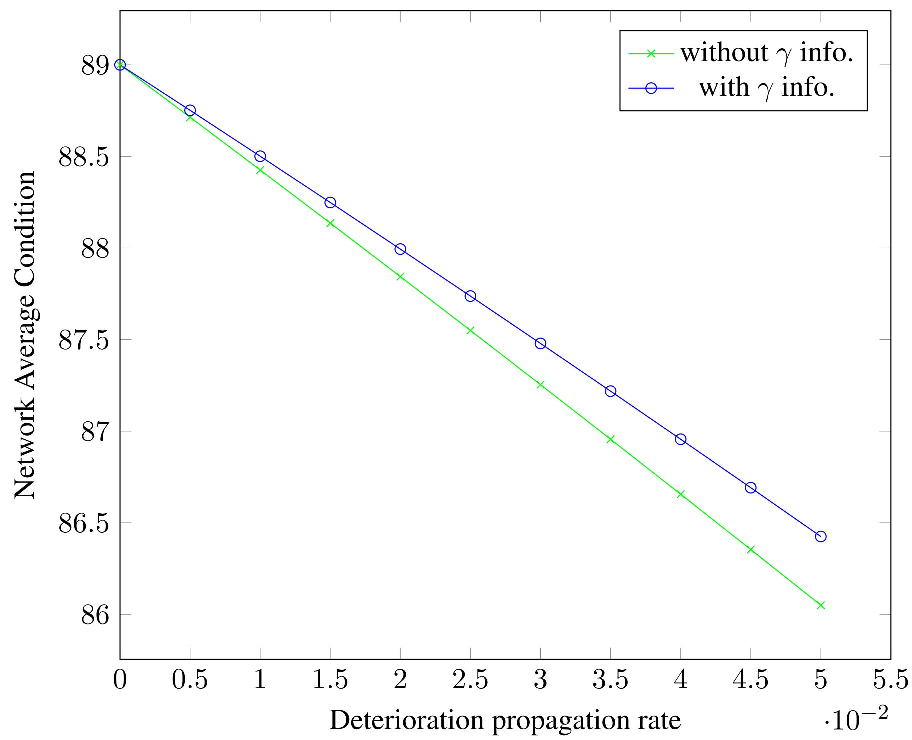

Figure 4: Deterioration propagation rate vs. network average condition ($N = 30$, $T = 4$, $B = \$500,000$, $g = 70$, $h = 0$, $\rho = 0.95$).

4.2 Example 2

In Example 2, a maintenance planning problem for a road network with up to 1,000 pavement sections was solved using heuristic algorithm. The purpose of this example is to test the computational efficiency of the proposed approximation method when it is applied to practical-sized problems. For demonstration purposes, it is assumed that the planning horizon is 3 years. The initial condition of each section is generated as random variables with a normal distribution of mean 80 and standard deviation 0.5. The maintenance treatments, deterioration rate, and deterioration propagation rate are assumed the same as the example 1. Although Example 2 uses random generating numbers to simulate the computational environment, the proposed method can be applied to any settings with real data.

Figure 5 shows the heuristic algorithm computing times observed against the number of sections in the network. The results of the computational experiment demonstrate that heuristic algorithm is able to solve practical size problems within a reasonable time, making it suitable for use when managing large numbers of sections and keeping track of section-specific condition data.

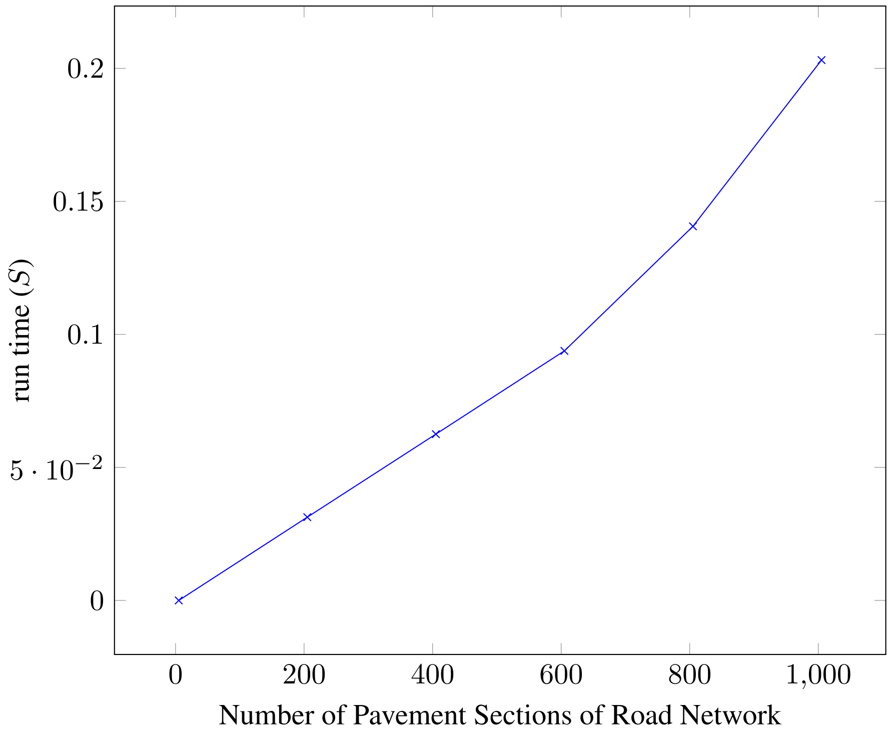

Figure 5: Computing time of heuristic algorithm ($N = 1000$, $T = 3$, $B = \$10,000$ per section, $\rho = 0.95$, $\gamma = 0.04$, $h = 0.9$, $g = 70$).

In Figure 6, the upper curve shows the network average condition obtained from exact solution by CPLEX and the lower curve shows its counterpart obtained by using the heuristic algorithm. We observe that the two curves are very close to each other and provide very good linear relationships. The gap between both curves increases when the number of sections increases but the largest difference is less than 1%. In other words, the obtained feasible solution is very close to the optimal one.

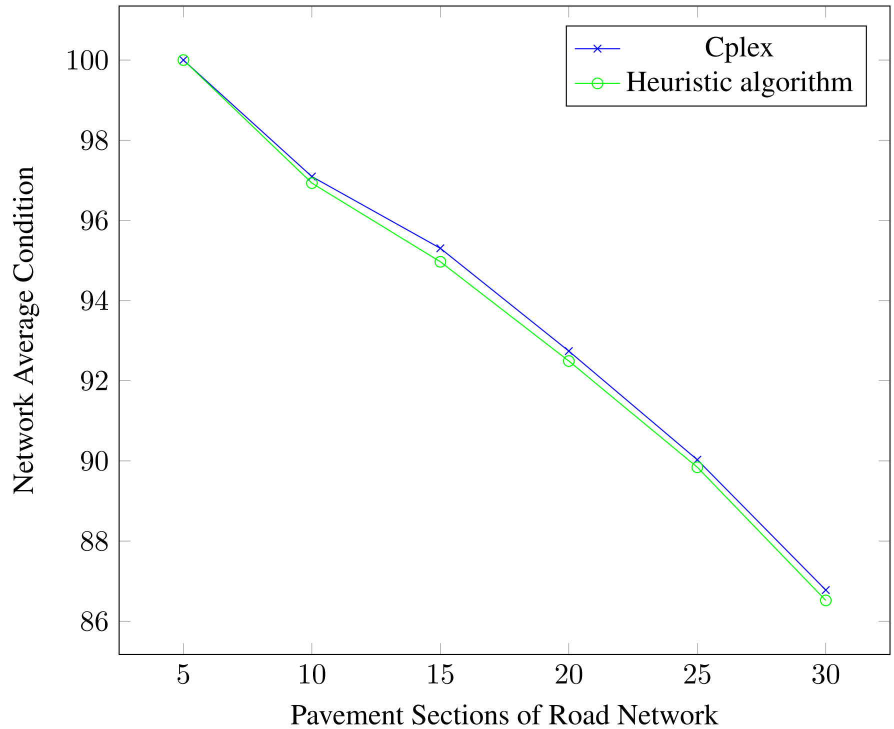

Figure 6: Pavement sections of road network vs. network average condition ($N = 30$, $T = 3$, $B = \$600,000$, $\rho = 0.95$, $\gamma = 0.04$, $h = 0.9$, $g = 70$).

5 CONCLUSION

This paper presented a mixed integer linear programming model that aims to optimize maintenance planning of an infrastructure system by considering the deterioration propagation between facilities. One of the important feature of this model is that it introduces the effect of deterioration propagation to complement the traditional deterioration process assumption. The model also takes into consideration constraints that a certain percentage of the system needs to be in good condition state. To our knowledge, no research has ever considered the deterioration propagation rate and percentage constraint behaviors simultaneously in a single maintenance optimization model. The model also features to restrict the condition of a facility to be within 0 to 100 using special order sets (SOS) variables.

One drawback of the 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, a heuristic algorithm was proposed. A case study based on pavement network is illustrated in this paper. The authors presented two examples in case studies to illustrate the characteristic of the proposed mixed integer linear programming model and to demonstrate the computational efficiency of developed heuristic algorithm. The case study confirms that the model incorporating the deterioration propagation could assist decision-makers in establishing better optimal solution. The influence of various factors such as the budget constraint, the deterioration propagation rate, and the minimum percentage coefficient were also investigated in the case study. The proposed method can help decision-makers effectively develop close-to-optimal maintenance and rehabilitation plans for real-world infrastructure systems.

Although road network examples are used in the case study, this research can be useful to other civil infrastructure networks. Many civil infrastructure network systems are distributed parallel to each other. For example, utility infrastructure of water, waste water, storm water, electricity, and communications are often co-located underneath the pavement or alongside the roadway. In the maintenance planning of these utilities often does not consider the deterioration propagation. The model with multiple years maintenance plan considering the deterioration propagation for all types of infrastructure network systems is one possible solution for this problem, which will be considered in future research to make the maintenance planning more efficient.

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