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Original Research Paper

# Considering deterioration propagation in transportation infrastructure maintenance planning

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## HIGHLIGHTS

- Deterioration propagation should be considered in asset management.
- Formulated an integer linear optimization model to find optimized maintenance scheduling.
- Models considering deterioration propagation performed better than those that don't.

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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 proposed model performs better than models without the deterioration propagation.



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## 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 transportation 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, Bernhardt and McNeil (2004) stated that pavements are interconnected through geography, which implied the economies of scale in contracting long stretches of pavement for rehabilitation and the diseconomies of scale in terms of the disruption to users. Gao and Zhang (2013b) 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. Rasmekomen and Parlikad (2013) conducted a study on optimizing maintenance plans for industrial assets by considering degradation and performance interaction between them.

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 (Huang, 2004). 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 (Dundulis et al., 2007). 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 transportation 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 and optimal control theory (Jido et al., 2008; Rashid and Tsunokawa, 2012), mixed nonlinear/linear integer programming (Gao and Zhang, 2008), reliability based maintenance/replacement models (Frangopol et al., 2001; Sanchez-Silva et al., 2005) are the most popular ones and have been extensively used for infrastructure maintenance optimization.

Network-level infrastructure maintenance planning problems are usually formulated as linear programming (LP) (Wu and Flintsch, 2009; Gao et al., 2012) or mixed integer linear/nonlinear programming (MIP) problems (Ng et al., 2009; Wang et al., 2003). In these models, a set of time points at which maintenance treatments might be applied is pre-defined. 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 (Chan et al., 1994; Fwa et al., 1994, 1996) and decomposition techniques (Dahl and Minken, 2008; Gao and Zhang, 2012; Karabakal et al., 1994) to handle large-scale maintenance planning problems. For example, Karabakal et al. (1994) and Dahl and Minken (2008) 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 sub problem solutions.

Some other researchers have used Markov based models to develop deterioration models. For example, Denysiuk et al. (2016) used Markov chain to model road deterioration process and solved for optimal maintenance schedule using genetic algorithm. In another research conducted by Gao and Zhang (2013a), Markov decision process (MDP) is used to calculate life cycle costs over service life of road. They

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**Table 1 – Notations.**

| Term | Definition | Range |
|---|---|---|
| Sets | | |
| $N$ | Set of infrastructure facilities, $N = \{1, 2, \cdots, n\}$ | |
| $M$ | Set of maintenance treatments, $M = \{1, 2, \cdots, k\}$ | |
| $T$ | Set of maintenance planning periods, $T = \{1, 2, \cdots, \upsilon\}$ | |
| Parameters | | |
| $B_t$ | Budget available for maintenance in the $t$th time period, $t \in T$ | $B_t \in \mathbb{R}^+$ |
| $c_m$ | The cost of applying the $m$th treatment, $m \in M$ | $c_m \in \mathbb{R}^+$ |
| $e_m$ | The effectiveness of the $m$th treatment, $m \in M$ | $e_m \in \mathbb{R}^+$ |
| $g$ | The threshold of good condition state. When $x_{it} \geq g$, the $i$th facility is considered to be in good condition state in the $t$th time period | $g \in \mathbb{R}^+$ |
| $\gamma$ | Deterioration propagation rate | $\gamma \in [0, 1]$ |
| $h$ | Minimum percentage of infrastructure facilities that are required to be in good condition state | $h \in [0, 1]$ |
| $\rho$ | Deterioration rate of facilities | $\rho \in [0, 1]$ |
| $s_i$ | Condition of the $i$th facility at the beginning of the planning horizon | $s_i \in \mathbb{R}^+$ |
| $R$ | A big number | Used 10,000 in case study |
| Variables | | |
| $x_{it}$ | Condition of the $i$th facility in the $t$th time period | $x_{it} \in \mathbb{R}^+$ |
| $x_{it1}, x_{it2}, x_{it3}$ | Variables representing $x_{it}$ in different domains. The purpose of using $x_{it1}$, $x_{it2}$ and $x_{it3}$ is for modeling purpose to restrict the condition of a facility to be within a specific range | $x_{it1}, x_{it2}, x_{it3} \in \mathbb{R}^+$ |
| $w_{it1}, w_{it2}, w_{it3}$ | Special ordered set (SOS) binary variables, which are used to restrict the condition of facility to between 0 and 100 | $w_{it1}, w_{it2}, w_{it3} \in \{0, 1\}$ |
| $y_{itm}$ | 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 $y_{itm} = 0$ | $y_{itm} \in \{0, 1\}$ |
| $z_{it}$ | Binary variables indicating if the condition of the $i$th facility is in good condition state in the $t$th time period | $z_{it} \in \{0, 1\}$ |

proposed a multi-objective maintenance model based on linear programming. This multi-objective modelling approach is used to optimize the solution with respect to different Pareto-fronts. Another bi-objective maintenance model proposed by Sousa et al. (2017) provides an optimum long-term maintenance schedule of infrastructure systems by minimizing costs and maximizing benefits.

## 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.

### 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 be maintained 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 Fig. 1. In this layout, each facility (except the ones at both ends) has two neighboring facilities.

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

Subject to

$$x_{it} = x_{it1} + x_{it2} + x_{it3} \quad i \in N,\ t \in T \tag{2}$$

$$w_{it1} + w_{it2} + w_{it3} = 1 \quad i \in N,\ t \in T \tag{3}$$

$$-R w_{it1} \leq x_{it1} \leq 0 \quad i \in N, t \in T \tag{4}$$

$$0 \leq x_{it2} \leq 100 w_{it2} \quad i \in N,\ t \in T \tag{5}$$

$$x_{it3} \geq 100 w_{it3} \quad i \in N, t \in T \tag{6}$$

$$x_{it3} \leq R w_{it3} \quad i \in N, t \in T \tag{7}$$

$$w_{it1}, w_{it2}, w_{it3} \in \{0, 1\} \quad i \in N, t \in T \tag{8}$$

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

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

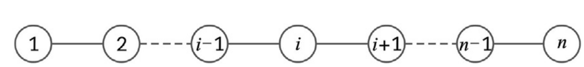


**Fig. 1 – Example layout of an infrastructure network.**

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

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

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

$$x_{it}=\rho(x_{i,t-1,2}+100w_{i,t-1,3})-\gamma(100-x_{i-1,t-1,2}-100w_{i-1,t-1,3})-\gamma(100-x_{i+1,t-1,2}-100w_{i+1,t-1,3})+\sum_{m\in M} e_m y_{itm} \quad i\in N\setminus\{1,n\}, t\in T\setminus\{1\} \tag{14}$$

$$x_{nt}=\rho(x_{n,t-1,2}+100w_{n,t-1,3})-\gamma(100-x_{n-1,t-1,2}-100w_{n-1,t-1,3})+\sum_{m\in M} e_m y_{ntm} \quad t\in T\setminus\{1\} \tag{15}$$

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

$$\sum_{i\in N}\sum_{m\in M} c_m y_{itm} \le B_t \quad t\in T \tag{17}$$

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

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

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

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

The objective function (1) of the proposed model is to maximize the average condition of the infrastructure systems over the planning horizon. The use of $x_{it2} + 100w_{it3}$ in the objective function is to ensure that only the [0, 100] part of the condition index is counted in evaluating the performance.

We assume that the condition indicators 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 0–100, special ordered sets of type 1 (SOS1) variables are used. The idea of constraints (2)–(8) is to ensure that even if the calculated condition of facility rises above 100 or below 0 in the calculations, only the part between 0 and 100 will be used for further evaluation. As shown in constraint (3), 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 (4) 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 in between 0 and 100, $w_{it2}$ will be 1 and $x_{it2}$ will represent the condition of the facility as shown in constraint (5). Constraints (6) and (7) ensure that even if the calculated condition of the facility is greater than 100, only 100 will be used for further calculation.

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.

In this model, we assume that the condition of a 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. These assumptions result in a linear deterioration model with a superposed effect from neighboring facilities. This methodology can also be applied to scenarios where the deterioration model is in a nonlinear form. As shown in Fig. 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 $\gamma(100 - w_{it3})$, where $\gamma$ is propagation rate and $x$ 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 0–100 when they are used to calculate next year's conditions.

Constraint (16) implies that only one treatment type is selected 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 $m$th treatment and $B_t$ is the available budget in year $t$.

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 (Zhang et al., 2010). 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 that on average at least $h$ percentage of facilities should be in good condition state for the entire planning period. Alternatively, this constraint can be broken down into different years to ensure that the $h$ percentage requirement is met each year.

Finally, constraints (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 $t$th time period. $z_{it}$ is a binary variable indicating whether the condition of the $i$th facility is greater than 70.

### 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

**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 | 3.0 |
| 3 | Light rehabilitation (LRhb) | 21 | 15 |
| 4 | Medium rehabilitation (MRhb) | 46 | 25 |
| 5 | Heavy rehabilitation (HRhb) | 110 | 40 |

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 ($\rho$), deterioration propagation rate ($\gamma$), minimum percentage requirement ($h$), and 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 $x$ is calculated using its previous year's condition $x_{i,t-1}$, deterioration rate $\rho$, and deterioration propagation $\gamma$.
      (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.

For demonstration purposes, the deterioration rate $\rho$ is set at 0.95 and the deterioration propagation rate $\gamma$ is set as 0.04. The selection of the deterioration rate is taken from previous studies (Jahanbakhsh et al., 2016; Ng et al., 2011). In these studies, the impact of neighboring facilities were calculated through incorporating infrastructure network structure into building deterioration model. 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 previous researches (Gao et al., 2010; Li and Madanu, 2009; Wang et al., 2003; Zhang et al., 2003).

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 rates in the deterioration process affects the performance of the model.

Fig. 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 $\gamma$ don't make a 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.

Fig. 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, Fig. 3 shows that, regardless of the budget, feasible solutions can always be obtained. However, the values of $h$ cannot 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

**Table 3 – Results of maintenance plan for 30 sections ($h = 0.9$, $g = 70$, $\rho = 0.95$, $B = \$500$ k).**

| Section No. | Deterioration propagation rate ($\gamma$) | Initial condition | Year 1 | | Year 2 | | Year 3 | |
|---|---|---|---|---|---|---|---|---|
| | | | Maintenance choice | Condition | Maintenance choice | Condition | Maintenance choice | Condition |
| 1 | 0.00 | 74 | 1 | 70 | 3 | 82 | 3 | 93 |
| | 0.04 | | 1 | 68 | 1 | 63 | 3 | 74 |
| 2 | 0.00 | 74 | 3 | 85 | 3 | 96 | 1 | 91 |
| | 0.04 | | 3 | 83 | 3 | 89 | 1 | 82 |
| 3 | 0.00 | 63 | 3 | 75 | 3 | 86 | 3 | 97 |
| | 0.04 | | 3 | 73 | 3 | 80 | 3 | 89 |
| 4 | 0.00 | 83 | 3 | 94 | 1 | 89 | 3 | 100 |
| | 0.04 | | 1 | 77 | 3 | 84 | 1 | 79 |
| 5 | 0.00 | 99 | 1 | 94 | 1 | 89 | 3 | 700 |
| | 0.04 | | 1 | 93 | 1 | 84 | 1 | 79 |
| 6 | 0.00 | 100 | 1 | 95 | 1 | 90 | 1 | 86 |
| | 0.04 | | 1 | 94 | 1 | 84 | 1 | 79 |
| 7 | 0.00 | 77 | 3 | 88 | 1 | 84 | 1 | 80 |
| | 0.04 | | 1 | 72 | 3 | 79 | 3 | 88 |
| 8 | 0.00 | 71 | 3 | 82 | 1 | 78 | 3 | 89 |
| | 0.04 | | 3 | 80 | 1 | 70 | 3 | 79 |
| 9 | 0.00 | 59 | 3 | 71 | 3 | 82 | 3 | 93 |
| | 0.04 | | 1 | 53 | 3 | 60 | 3 | 70 |
| 10 | 0.00 | 61 | 3 | 73 | 3 | 84 | 3 | 95 |
| | 0.04 | | 3 | 71 | 3 | 78 | 1 | 72 |
| 11 | 0.00 | 88 | 1 | 84 | 1 | 79 | 1 | 75 |
| | 0.04 | | 3 | 96 | 1 | 86 | 1 | 80 |
| 12 | 0.00 | 77 | 3 | 88 | 3 | 99 | 1 | 94 |
| | 0.04 | | 1 | 71 | 3 | 78 | 1 | 72 |
| 13 | 0.00 | 63 | 3 | 75 | 3 | 86 | 3 | 97 |
| | 0.04 | | 3 | 73 | 3 | 79 | 3 | 88 |
| 14 | 0.00 | 72 | 3 | 83 | 1 | 79 | 3 | 90 |
| | 0.04 | | 3 | 81 | 1 | 72 | 3 | 82 |
| 15 | 0.00 | 73 | 1 | 69 | 3 | 81 | 3 | 92 |
| | 0.04 | | 3 | 82 | 3 | 88 | 3 | 97 |
| 16 | 0.00 | 73 | 3 | 84 | 3 | 95 | 1 | 90 |
| | 0.04 | | 3 | 82 | 3 | 87 | 3 | 97 |
| 17 | 0.00 | 62 | 3 | 74 | 3 | 85 | 3 | 96 |
| | 0.04 | | 3 | 70 | 3 | 76 | 3 | 85 |
| 18 | 0.00 | 40 | 3 | 53 | 3 | 65 | 3 | 77 |
| | 0.04 | | 3 | 51 | 3 | 60 | 3 | 70 |
| 19 | 0.00 | 94 | 1 | 89 | 1 | 85 | 1 | 81 |
| | 0.04 | | 3 | 100 | 1 | 91 | 1 | 84 |
| 20 | 0.00 | 100 | 1 | 95 | 1 | 90 | 1 | 86 |
| | 0.04 | | 1 | 94 | 1 | 89 | 1 | 83 |
| 21 | 0.00 | 77 | 1 | 73 | 3 | 84 | 1 | 80 |
| | 0.04 | | 3 | 88 | 1 | 80 | 3 | 90 |
| 22 | 0.00 | 100 | 1 | 95 | 1 | 90 | 1 | 86 |
| | 0.04 | | 1 | 94 | 3 | 100 | 1 | 93 |
| 23 | 0.00 | 97 | 1 | 92 | 1 | 88 | 1 | 83 |
| | 0.04 | | 1 | 92 | 1 | 83 | 1 | 79 |
| 24 | 0.00 | 90 | 1 | 86 | 3 | 96 | 1 | 91 |
| | 0.04 | | 3 | 100 | 1 | 91 | 1 | 85 |
| 25 | 0.00 | 94 | 1 | 89 | 1 | 85 | 3 | 96 |
| | 0.04 | | 1 | 89 | 1 | 84 | 1 | 79 |
| 26 | 0.00 | 100 | 1 | 95 | 1 | 90 | 1 | 86 |
| | 0.04 | | 1 | 95 | 1 | 85 | 1 | 80 |
| 27 | 0.00 | 94 | 1 | 89 | 1 | 85 | 1 | 81 |
| | 0.04 | | 1 | 89 | 1 | 81 | 1 | 75 |
| 28 | 0.00 | 100 | 1 | 95 | 1 | 90 | 1 | 86 |
| | 0.04 | | 1 | 94 | 1 | 85 | 3 | 95 |
| 29 | 0.00 | 90 | 1 | 86 | 1 | 81 | 1 | 77 |
| | 0.04 | | 1 | 84 | 3 | 89 | 1 | 82 |
| 30 | 0.00 | 65 | 3 | 77 | 3 | 88 | 3 | 99 |
| | 0.04 | | 1 | 61 | 1 | 50 | 3 | 62 |

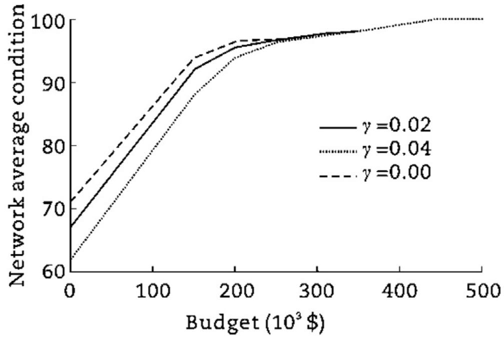


**Fig. 2 – Budget vs. network average condition for different deterioration propagation rates ($N = 30$, $T = 4$, $g = 70$, $h = 0$, $\rho = 0.95$).**

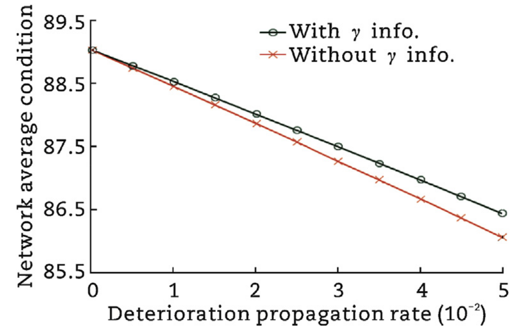


**Fig. 4 – Deterioration propagation rate vs. network average condition ($N = 30$, $T = 4$, $B = \$500,000$, $g = 70$, $h = 0$, $\rho = 0.95$).**

should be in good condition state. As can be seen in Fig. 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 $h$. Fig. 3 also shows that when budget is large enough, the value of $h$ does not make a difference in the optimal solution.

To understand the importance of considering deterioration propagation rate while planning maintenance treatments, a comparative study is conducted between two scenarios and results are presented in Fig. 4. This comparison involves two steps. In the first step, maintenance treatment plan was obtained by solving the proposed constraints (1)–(21). While the treatment plan was calculated by solving the proposed model with the real propagation rate in scenario 1 (with $\gamma$ info.), scenario 2 (without $\gamma$ info.) treatments were obtained by solving the proposed model with propagation rate of 0. In the second step, the network average condition is calculated using the obtained maintenance treatments and the real propagation rate. It can be seen in Fig. 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.

### 4.2. *Example 2*

In Example 2, a maintenance planning problem for a road network with up to 1000 pavement sections was solved using heuristic algorithm. Because of the complexity of the proposal model, a practical network cannot be solved on a desktop computer within a reasonable time limit. 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 of 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.

Fig. 5 shows the heuristic algorithm computing times observed against the number of section sin 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. In the example used in Fig. 5, available budget $B$ limited to a maximum dollar value of 10,000 times the number of sections.

In Fig. 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

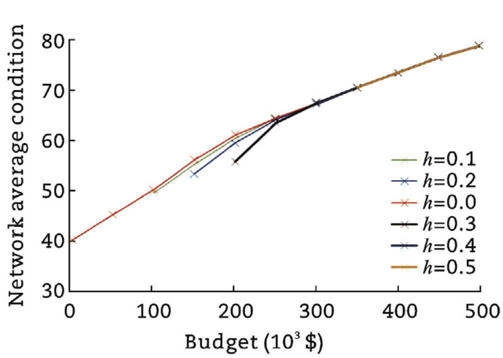


**Fig. 3 – Budget vs. network average condition ($N = 30$, $T = 3$, $\rho = 0.95$, $\gamma = 0.04$, $g = 70$).**

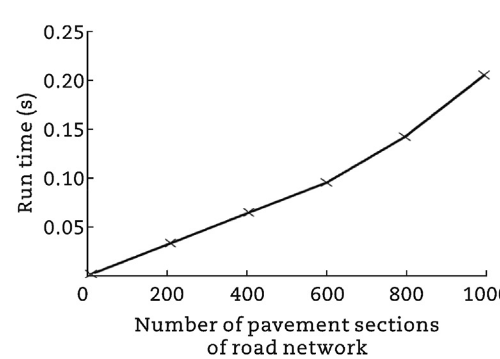


**Fig. 5 – Computing time for heuristic algorithm ($T = 3$, $B = \$10,000$ per section, $\rho = 0.95$, $\gamma = 0.04$, $h = 0.9$, $g = 70$).**

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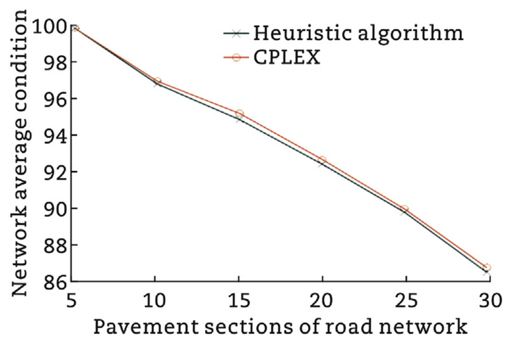


**Fig. 6 – Performance comparison of CPLEX and heuristic algorithms ($N = 30$, $T = 3$, $B = \$600{,}000$, $\rho = 0.95$, $\gamma = 0.04$, $h = 0.9$, $g = 70$).**

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.

## 5. Conclusions

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 features 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.

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. Two examples were presented in the case study section, which 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 solutions. 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. Deterioration propagation is often not considered while planning maintenance activities for these utilities. One possible solution for this problem is to prepare a model considering deterioration propagation for all types of infrastructure network systems. This can be considered for future research.

## Conflict of interest

The authors do not have any conflict of interest with other entities or researchers.

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