Incorporating Delay Effects into Airport Runway Pavement Management Systems

Bo Zou\textsuperscript{1}; Samer Madanat\textsuperscript{2}

**Abstract:** This paper presents an approach to address pavement management decision problems at airports with multiple runways. It relaxes some of the underlying assumptions made in previous studies, and explicitly considers time requirement for runway reconstruction, deterioration dependence on traffic levels, and the growth of traffic demand over time. A finite-horizon dynamic program is formulated to investigate the interplays among M&R action time, functional interdependence between runways, and traffic growth. Results from computational studies reveal these interplays, in particular the trade-off between present M&R action and delay cost and long-term benefits brought by significantly upgrading pavement condition through reconstructing runways. Sensitivity analyses suggest that baseline demand, demand growth rate, and the parameter differentiating traffic-dependent transition probabilities significantly affect optimal M&R decisions and total expected cost-to-go.

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Introduction

Airport runway infrastructure management refers to the process of making decisions concerning the maintenance and repair (M&R) actions to apply to runways. The objective of making these decisions is to ensure both the functional and operational performance of runways, taking into account agency cost, user costs and M&R associated delay cost. The latter stems from the functional interdependence of runways, and the fact that a certain amount of time is required for M&R actions to be completed.

In road pavement management research, functional interdependence has become a research topic of increasing importance. One stream of studies is related to scheduling planned M&R activities to minimize traffic delays. Fwa et al. (1998) employ genetic algorithms to solve a 20-section road network problem. Chang et al. (2000) adopt dynamic traffic assignment models and a Tabu search methodology to minimize traffic delays caused by work zone combinations. Simulation has been used to address similar problems (Sanford-Bernhardt and McNeil 2004). Wang et al. (2002) develop a hybrid scheduling methodology combining genetic algorithms and microscopic traffic simulation.

A second stream of studies accounts for functional interdependence in the M&R planning process by jointly minimizing agency and user delay cost. Adey et al. (2003)
determine the optimal policy that minimizes the total cost on a transportation network consisting of five bridges, taking into consideration the functional role and performance of the bridges in the network and the consequences if an adequate level of service is not provided. Hajdin and Lindenmann (2007) present a network optimization model that yields minimum overall agency and user cost through intervention bundles on complementary sections in a road corridor. Durango and Sarutipand (2007) formulate quadratic programs to study both substitutable and complementary structures in transportation infrastructure networks, and demonstrate that optimality requires coordinating M&R interventions for clusters of facilities in transportation systems.

Among practical projects where delay is of particular concern, researchers find that the delay elements are surprisingly large in the overall cost. For example, when developing work zone models, Moavenzadeh (1971) and Butler (1973) find that delay costs alone overwhelm the agency costs associated with pavement reconstruction and rehabilitation. HDM III, a widely used Highway design and Maintenance Model, shows that the user costs represent more than 85% of the total discounted project costs over a 20-year period (Watanatada et al., 1988).

In the airport runway pavement context, functional interdependence refers to traffic re-allocation due to M&R actions and associated runway closure. This interdependence has been qualitatively recognized in McNerney and Harrison (1995). At Dallas/Fort Worth International Airport the Air Transport Association estimated the cost of closing runway 18R/36L in 1990 to range between $110,000 and $131,000 per day, due to airline delays (Lary et al. 1991). The substantial cost notwithstanding, efforts to
explicitly incorporate delay into the M&R activity planning process are rarely found in the airport pavement management research literature.

In an attempt to fill this gap, this paper investigates how interdependence among runways impact M&R decision making process. We relax some of the underlying assumptions made in the literature. First, we explicitly recognize that M&R actions take time to implement. Specifically, reconstructing a runway involves fundamental changes of pavement structure; its duration cannot be ignored in M&R planning. Second, user costs, in this paper, depend not only on pavement condition but also on the extent of traffic on each runway. This must be accounted for because M&R actions require traffic redistribution, generating M&R delays and cost. The third relaxation is that traffic is not assumed to stay constant over time. To better reflect the reality in air travel, a growth rate is assumed. The problem is formulated as a dynamic programming problem with a finite horizon. The finite-horizon formulation allows for identifying the deterioration and M&R decision making for each runway individually. Although a single airport may contain multiple runways, the number is relatively small. The often-mentioned “curse-of-dimensionality” issue in road network infrastructure management problems can be largely avoided. Dynamic programming provides an attractive framework for analyzing the interplay among M&R action time, functional interdependence between runways, and traffic growth at the airport.

The rest of this paper is organized as follows. The deterioration process and the quantification of delay effects are described in the next two sections. We then present a mathematical formulation of the problem, which is followed by numerical studies and sensitivity analyses. In the end, conclusions are given and future research is suggested.
Deterioration Process

An essential part in modeling M&R decision-making is to characterize the pavement deterioration process. We adopt Markovian deterioration models, which are often specified as a set of transition probability matrices. Each transition matrix corresponds to one M&R action, in which the element \((i, j)\) represents the transition probability from state \(i\) in the current time period to state \(j\) in the next time period. We expect traffic loading to affect runway deterioration. We assume there is one single, medium-sized aircraft type flying into and out of the airport. Traffic loading can then be translated into the number of aircraft operations on each runway. A transition probability, \(p_{i,j}(a,q)\), is then a function of the transitioning states pair \((i, j)\), the M&R action \(a\), and the traffic loading \(q\). To keep our problem tractable without losing realism, we assume that \(p_{i,j}(a,q)\) is a step-wise function of \(q\), with \(q_1\) and \(q_2\) being the thresholds for low, medium, and high traffic levels. For a given combination of \(i, j, a,\) and \(q\), the transition probabilities are given by:

\[
p_{i,j}(a,q) = \overline{p}_{i,j}(a,m(q)) \quad \text{where} \quad m(q) = \begin{cases} 
1 & \text{if } 0 < q < q_1 \\
2 & \text{if } q_1 \leq q < q_2 \\
3 & \text{if } q \geq q_2 
\end{cases} \quad (1)
\]

The discretization of \(q\) into \(m(q)\) reduces the number of transition matrices to \(3 \times B\), where \(B\) is the number of M&R actions available. Three actions are considered:
doing-nothing, maintenance, and reconstruction. The focus of the paper is only flexible pavement. We further assume that there are four condition states (so the dimension of each transition matrix is 4 × 4), and that the unit planning time is three months. Following Mayet and Madanat (2002), the condition state may stay the same or decrease by one unit when doing-nothing between two consecutive planning periods (when already in the worst state, condition does not change without maintenance or reconstruction). If maintenance is chosen, there is a non-zero probability for the runway condition to improve to a better state unless the current condition is in the best state. If reconstruction is performed, the runway condition is upgraded to the best state regardless of the original conditions. Let \( a = 1, 2, 3 \) denote doing-nothing, maintenance, and reconstruction respectively. Table 1 shows the general form of the transition probability matrices:

<table>
<thead>
<tr>
<th>Action</th>
<th>Transition matrix</th>
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| Doing-nothing \((a=1)\)     | \[
P(1, q) = \begin{bmatrix}
p_{11}(1, q) & p_{12}(1, q) \\
p_{22}(1, q) & p_{23}(1, q) \\
p_{33}(1, q) & p_{34}(1, q) \\
1 & 1
\end{bmatrix}
\]
| \[
\bar{P}(1, m(q)) = \begin{bmatrix}
\bar{p}_{11}(1, m(q)) & \bar{p}_{12}(1, m(q)) & \bar{p}_{13}(1, m(q)) & \bar{p}_{14}(1, m(q)) \\
\bar{p}_{21}(1, m(q)) & \bar{p}_{22}(1, m(q)) & \bar{p}_{23}(1, m(q)) & \bar{p}_{24}(1, m(q)) \\
\bar{p}_{31}(1, m(q)) & \bar{p}_{32}(1, m(q)) & \bar{p}_{33}(1, m(q)) & \bar{p}_{34}(1, m(q)) \\
1 & 1 & 1 & 1
\end{bmatrix}
\] |
As traffic increases, there is a greater likelihood of transitioning from a better state to a worse one. As a consequence it is more probable for the runway condition to transition to a lower state. Such effects are captured by a new parameter $\theta$. For doing nothing,

$$\overline{P}(1,m(q) + 1) = \begin{bmatrix} \overline{p}_{11}(1,m(q)) - \theta & \overline{p}_{12}(1,m(q)) + \theta \\ \overline{p}_{22}(1,m(q)) - \theta & \overline{p}_{23}(1,m(q)) + \theta \\ \overline{p}_{33}(1,m(q)) - \theta & \overline{p}_{34}(1,m(q)) + \theta \\ \overline{p}_{43}(1,m(q)) - \theta & \overline{p}_{44}(1,m(q)) + \theta \\ \end{bmatrix}$$

where $m(q) = 1, 2$

(2)

For maintenance, we assume that the effect of $\theta$ is as shown below:
\[
\bar{p}(2,m(q)+1) = \begin{bmatrix}
\bar{p}_{11}(2,m(q)) - \theta & \bar{p}_{12}(2,m(q)) + \theta \\
\bar{p}_{21}(1,m(q)) - \theta / 2 & \bar{p}_{22}(1,m(q)) - \theta / 2 & \bar{p}_{23}(1,m(q)) + \theta \\
\bar{p}_{32}(1,m(q)) - \theta / 2 & \bar{p}_{33}(1,m(q)) - \theta / 2 & \bar{p}_{34}(1,m(q)) + \theta \\
\bar{p}_{43}(1,m(q)) - \theta & \bar{p}_{44}(1,m(q)) + \theta
\end{bmatrix}
\]
\[m(q) = 1,2\]

(3)

Quantifying the Delay Effect

Since delay occurs when normal runway operations are disrupted due to M&R actions, it is necessary to specify the duration of such actions. We assume reconstruction takes 3 months, during which no aircraft operations are allowed on that runway. The 3-month period coincides with the unit planning time and is a realistic duration for reconstruction in the flexible pavement context. On the other hand, maintenance is assumed not to cause any operational interruption. Hayhoe et al. (1998) shows that maintenance work can be carried out at night when the airport is under curfew; therefore the use of runways over the rest of the day will not be affected.

A runway is closed to aircraft operations if reconstruction is chosen, resulting in redistribution of traffic over the available runways. Assuming that overall travel demand at the airport does not change as a function of M&R actions, closing a runway can lead to a temporary shortage of capacity, and therefore delays. Reconstruction of all runways simultaneously means operational disruption rather than traffic delay. We assume that simultaneous reconstruction of all runways, or complete closure of the airport, is not permitted.
Let $q$ denote the total traffic volume for each 3-month period (aircraft/quarter). $N$ indicates the number of runways. All runways have the same capacity $q_0$ (aircraft/quarter). $a_n$ is the action taken for the $n$th runway where $n = 1, 2, \ldots, N$ (for simplicity, the subscript $t$ is omitted). An availability variable $X_n$ is used for runway $n$:

$$X_n = \begin{cases} 0 & \text{if } a_n = 3 \\ 1 & \text{otherwise} \end{cases}$$  \hspace{1cm} (4)$$

The total number of runways in service is then $\sum_{n=1}^{N} X_n$. Although discrepancies exist between peak and non-peak hours in terms of demand, for many airports this is shown not to be very significant (Fig. 1). For simplicity, we assume uniform arrivals of aircraft during operating hours (e.g. 7am – 11pm). Given the service time length for one day ($d$ hours), the average arrival demand, measured in aircraft/hour, assigned to each available runway is

$$\frac{q}{90 \cdot d \cdot \sum_{n=1}^{N} X_n}.$$  

where each quarter is assumed to be 90 days long.

When a runway is in service and delay occurs, the cumulative arrival demand and capacity with respect to time can be schematically represented by Fig. 2. The area between the actual demand and capacity is the total delay. Using the geometric relations in Fig. 2, the aircraft delay time on that runway in one day can be expressed as:
Such delays translate into costs, including airlines’ additional operating expenses, in terms of extra fuel, crew service time, and disruption of original schedules. The costs also include the passenger-side cost due to the lengthening of travel time. Let $c_1$ ($$/hr$$) denote the airline cost part for each hour of delay. The passenger delay cost is obtained by multiplying the passenger value of time $c_2$ ($$/passenger-hour$$) and the average number of passengers on an airplane $M$ (passengers/plane). Aggregating delay over all in-service runways throughout one quarter, and multiplying it by the sum of airline and passenger cost per unit delay time, we obtain the total delay cost as

$$
\begin{align*}
\text{Quarterly airport delay cost with M & R} &= \left\{ \begin{array}{ll}
0 & \text{if } q \sum_{n=1}^{N} X_n \leq q_0 \\
\frac{qd}{180} \left( \frac{q}{q_0} \sum_{n=1}^{N} X_n \right) \left( \frac{q}{q_0} \sum_{n=1}^{N} X_n - 1 \right) & \text{if } q \sum_{n=1}^{N} X_n > q_0
\end{array} \right.
\end{align*}
$$

(6)
Fig. 1. Cumulative number of arrivals for a sample day schedule at Baltimore Airport

Source: FAA Aviation System Performance Metrics (ASPM) Database

Fig. 2. Illustration of delay effects

It is important to recognize that the delay cost above can be attributed to both M&R actions taken and traffic growth. The associated delays are denoted respectively as M&R delay and delay purely due to demand growth. In M&R decision-making, only the
former is relevant for optimization and should be extracted. Delay from growth does not change M&R policies. To do this, we first quantify the delay purely due to demand growth, and then subtract it from the overall delay. Following the same approach described above, the amount of delay that is purely due to demand growth is obtained, assuming there is no M&R intervention:

\[
\begin{cases}
0 & \text{if } q/N \leq q_0 \\
(c_1 + c_2 \cdot M) \cdot \frac{q d}{2} \left( \frac{q}{q_0 N} - 1 \right) & \text{if } q/N > q_0
\end{cases}
\]  

(7)

In order to derive the expression for M&R delay cost using Eqs. (6) and (7), we need to introduce two additional variables \( S_t \) and \( \overline{S}_t \) that indicate whether the overall demand, relative to the available capacity with and without M&R actions, causes delay in time period \( t \):

\[
S_t = \begin{cases}
0 & \text{if } q_t / \sum_{n=1}^{N} X_n \leq q_0 \\
1 & \text{if } q_t / \sum_{n=1}^{N} X_n > q_0
\end{cases}
\]  

(8)

\[
\overline{S}_t = \begin{cases}
0 & \text{if } q_t / N \leq q_0 \\
1 & \text{if } q_t / N > q_0
\end{cases}
\]  

(9)

The total delay cost, attributable to M&R actions, is:
\[
c_{d,t} = (c_1 + c_2 \cdot M) \frac{q_d}{2} \left\{ \frac{1}{q_0} \sum_{n=1}^{N} X_n - 1 \right\} S_t - \left( \frac{q_d}{q_0 N} - 1 \right) \bar{S}_t \]  

\text{(10)}

**Problem Formulation**

The M&R decision-making problem is solved by dynamic programming. The length of the planning horizon is set to \( T \) periods, during which there is no capacity expansion. At each time period \( t (t=1\ldots T) \), the objective is to minimize the expected present value of the total cost-to-go, over all runways \( n = 1\ldots N \).

\[
V_t(I, q_t) = \min_{A} \left( c(A, I, q_t) + \alpha \sum_{j_1} \sum_{j_2} \ldots \sum_{j_N} \prod_{n=1}^{N} p_{i_n, j_n} (a_n, q_{nt}) \cdot V_{t+1}(J, q_{t+1}) \right) 
\]

\text{s.t.} \sum_{n=1}^{N} X_n > 0  

\text{(11)}

where \( A = (a_1, a_2, \ldots, a_N) \), \( I = (i_1, i_2, \ldots, i_N) \), \( J = (j_1, j_2, \ldots, j_N) \) are the set of actions taken in time period \( t \) and the set of condition states at time \( t \) and \( t+1 \) respectively, for runways 1 to \( N \). \( q_t \) represents the total demand in quarter \( t \).

\[
q_{nt} = q_t \frac{X_n}{\sum_{n=1}^{N} X_n} \]  

specifies the quarterly traffic volume on the \( n \)th runway. \( \alpha \) denotes the discount amount factor, transforming the expected cost-to-go of the next quarter to present values.
The left-hand-side, $V_t(I, q_t)$, represents the expected cost-to-go at time $t$, given condition states $I = (i_1, i_2, ..., i_N)$ of runways and total demand $q_t$. On the right hand side, inside the $\min$ operator, $c(A, I, q_t)$ represents the cost incurred at time period $t$, when action set $A$ is applied to the airport. It includes three components: agency M&R action cost $c_a(A, I)$, user depreciation cost $c_w(A, I, q_t)$, and user M&R delay cost $c_d(A, q_t)$.

Here, $c_a(A, I)$ is the sum of M&R action cost across all runways, which is a function of the M&R actions taken ($A$) and runway conditions ($I$). $c_w(A, I, q_t)$ refers to aircraft depreciation caused by wear-and-tear due to poor pavement conditions. For each runway, the cost is the product of the traffic level and a unit depreciation cost which depends on runway pavement conditions. Since the flight traffic on each runway is determined by the M&R decisions and the total traffic, the overall user depreciation cost $c_w$ is a function of $A$, $I$, and $q_t$. The M&R delay cost $c_d$ is expressed in (10). As $X_n$’s, $S_t$, and $\overrightarrow{S}_t$ all depend on the M&R actions taken, $c_d$ is a function of $A$ and $q_t$. Summing, we have,

$$c(A, I, q_t) = c_a(A, I) + c_w(A, I, q_t) + c_d(A, q_t)$$

Expanding the first two terms on the right hand side of Eq. (12) following the above discussion and substituting Eq. (10) for the third term yield:
\[ c(\mathbf{A}, \mathbf{I}, q_t) = \sum_{n=1}^{N} c_{\text{ac}}(a_n, i_n) + \sum_{n=1}^{N} c_{\text{wc}}(\mathbf{A}, i_n, q_t) + c_d(\mathbf{A}, q_t) \]

\[ = \sum_{n=1}^{N} c_{\text{ac}}(a_n, i_n) + \sum_{n=1}^{N} c_{\text{wc}}^w(i_n) \left[ q_t \left( \frac{X_n}{\sum_{n=1}^{N} X_n} \right) \right] \]

\[ + (c_1 + c_2 \cdot M) \frac{q_t d}{2} \left\{ (\frac{q_t}{q_0} \sum_{n=1}^{N} X_n - 1) \bar{S}_t - (\frac{q_t}{q_0N} - 1) \bar{S}_t \right\} \]

\[ = \sum_{n=1}^{N} c_{\text{ac}}(a_n, i_n) + q_t \frac{\sum_{n=1}^{N} c_{\text{wc}}^w(i_n) X_n}{\sum_{n=1}^{N} X_n} \]

\[ + (c_1 + c_2 \cdot M) \frac{q_t d}{2} \left\{ (\frac{q_t}{q_0} \sum_{n=1}^{N} X_n - 1) \bar{S}_t - (\frac{q_t}{q_0N} - 1) \bar{S}_t \right\} \] (13)

where \( c_{\text{ac}}(a_n, i_n) \) is the agency M&R action cost on the \( n \)th runway if action \( a_n \) is applied and the runway condition state is \( i_n \). \( c_{\text{wc}}^w(i_n) \) denotes the unit depreciation cost (measured in $/flight) if a runway is in condition \( i_n \), and \( q_t \frac{X_n}{\sum_{n=1}^{N} X_n} = q_{nt} \).

The second term inside the \( \min \) operator in Eq. (11),

\[ \alpha \sum_{j_1} \sum_{j_2} \ldots \sum_{j_N} \left[ \prod_{n=1}^{N} p_{s_n, j_n}(a_n, q_{nt}) \right] \cdot V_{t+1}(\mathbf{J}, q_{t+1}), \] is the present value of the expected cost-to-go in the next period. Recall from section two that the transition probability \( p_{s_n, j_n} \) is a function of both the action taken \( (a_n) \) and the traffic volume \( (q_{nt}) \). Given at period \( t \), the initial set of runway condition states \( \mathbf{I} = (i_1, i_2, ..., i_N) \), the M&R actions applied \( \mathbf{A} = (a_1, a_2, ..., a_N) \), and the traffic on each runway \( q_{nt} \ (n = 1, ..., N) \), and assuming
that the runways deterioration processes are independent of each other, the probability of
the set of runway condition states being \( J = (j_1, j_2, \ldots, j_N) \) in period \( t+1 \)
is \( \prod_{n=1}^{N} p_{s_{t+n}}(a_n, q_{nt}) \).

\( J = (j_1, j_2, \ldots, j_N) \) then becomes the initial set of runway condition states for period
\( t+1 \), and the corresponding expected cost-to-go is \( V_{t+1}(J, q_{t+1}) \). Thus at period \( t \), to obtain
the expected present value of the cost-to-go for the next period, it suffices to enumerate
the set \( J \) and calculate the discounted expected value of \( V_{t+1}(J, q_{t+1}) \), i.e.

\[
\alpha \sum_{j_1} \sum_{j_2} \ldots \sum_{j_N} \left[ \prod_{n=1}^{N} p_{s_{t+n}}(a_n, q_{nt}) \right] V_{t+1}(J, q_{t+1}).
\]

**Computational Study**

The objective of the computational study is to illustrate the interplay among M&R
action time, runway functional interdependence, and traffic growth in the M&R decision
making process. To this end, we solve the dynamic programming problem for a base case
and examine the results obtained. We then conduct a set of sensitivity analyses to
investigate the impact of different parameters on the solutions. Although some
parameters used in the computational study are not derived from field data, we expect the
results presented here to provide at least qualitative insights about such interplays, and
the relation between parametric changes and optimal policies.
Data

We assume the airport under study has two runways dedicated to landing operations, with an average daily traffic of 300 flights per day in the baseline year. The capacity, measured in daily airport arrival rate (AAR), is set at 600 operations per day. Checking with the actual flight traffic and AAR profiles reveals that the airport described above is comparable to a medium-sized U.S. airport.\(^3\) We assume a single aircraft type with a constant load factor, with each flight having 75 passengers onboard. This suggests an annual inbound traffic volume of 8.2 million passengers in the baseline year.\(^4\)

The planning horizon \(T\) is set to be 40 time periods, or 10 years (since our unit time is 3 months). Flight traffic is projected to witness a 2% increase annually. We introduce seasonal imbalance of traffic by assuming that for each year, traffic in the 3\(^{rd}\) and 4\(^{th}\) quarters is 5% higher than that in the first two quarters. The annual discount rate is 0.02 (and thus for each quarter \(\alpha = 1/(1+0.02/4)=0.995\)). Since traffic volume is

\(^3\) This comparison is made using the FAA Airport System Performance Metrics (ASPM) database. For example, the average daily flight traffic (operations/day), daily AAR (operations/day), and the number of runways at four medium-sized U.S. airports in August 2007 are: Washington National (daily traffic: 385, AAR: 588, No. runways: 3), Cleveland (daily traffic: 313, AAR: 662, No. runways: 3), Baltimore (daily traffic: 332, AAR: 651, No. runways: 4), Chicago Midway (daily traffic: 292, AAR: 588, No. runways: 5).

\(^4\) This annual passenger traffic number is also comparable with those of medium-sized U.S. airports. Considering the rough equivalence of inbound and outbound traffic, we can use passenger enplanements to make a first-order comparison. In 2007, the annual passenger enplanements (in millions) at the four airports in footnote 3 are: Washington National: 9.0; Cleveland: 5.8; Baltimore: 10.5; Chicago Midway: 9.1 (FAA, 2011).
discretized when determining which transition probability applies to a given aircraft operation density, it suffices to consider the transformed transition matrix $\bar{P}$ rather than the original matrices. We first illustrate the matrices where traffic is at the “low” level, i.e. $\bar{P}(a,1), a = 1, 2, 3$, as shown in Table 2. Compared to doing nothing, maintenance reduces the probability of transitioning to a lower state. Reconstruction resets runway to the best condition state. The salvage values at the end of the planning period for states 1 to 4 (from the best to the worst) are -6, -4, -2, and 0 million dollars, respectively, where the negative sign indicates a benefit.

**Table 2.** Transformed Transition Probabilities when Traffic Volume is Low

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<th>3</th>
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As discussed earlier, the transition probabilities also depend on the traffic volume, whose effect is captured by the parameter $\theta$ in the transition probability matrices. We let $\theta = 0.05$, and define the “low” traffic volume to be less than $q_1 = 1.4 \times 10^4$ aircraft per quarter-runway, the “high” volume to be greater than $q_2 = 1.6 \times 10^4$ aircraft per quarter-runway, and the “medium” traffic volume to be between $q_1$ and $q_2$. As an example, the transition probabilities for the do-nothing case, under medium and high traffic density, are:

**Table 3.** Transformed Transition Probabilities for Doing-nothing at Medium and High Traffic Levels

<table>
<thead>
<tr>
<th>Do nothing (traffic volume: medium)</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.45</td>
<td>0.55</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.45</td>
<td>0.55</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>0.45</td>
<td>0.55</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td>0.45</td>
<td>0.55</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Do nothing (traffic volume: high)</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.4</td>
<td>0.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.4</td>
<td>0.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.4</td>
<td>0.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

The costs associated with M&R actions are presented in Table 4. The maintenance cost increases as the runway condition worsens. The reconstruction cost does not depend on the original condition state. The user depreciation cost (Table 5) refers primarily to aircraft wear-and-tear expenses and is thus a function of runway
condition. A major source of wear-and-tear is fatigue. Empirical evidence suggests that the fatigue effect of vertical acceleration increases non-linearly with runway surface unevenness (Gervais 1991). In the absence of exact cost relationship, we adopt the non-linear increasing cost values in Table 5.

The cost factors employed to quantify the delay effects are based on GRA Inc. et al. (2004), where the estimated cost per block hour for a medium-sized aircraft (150 seats) is about $4000. Anticipating delays, ground delay programs (GDP) may be initiated, in which case inbounding flights are delayed on the ground at the origin airport, reducing the unit delay cost to about one-third to one-fourth of the cost if delay happened in the air. To account for this fact we use $1000/hr in the following study. On the passenger side, GRA Inc. et al. (2004) provides a standard value of time for air travelers, estimated at $25 per hour.

<table>
<thead>
<tr>
<th>Table 4. M&amp;R Action Cost (Million $/Runway)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condition state</td>
</tr>
<tr>
<td>-----------------</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 5. User Cost Associated with Depreciation ($/Aircraft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condition state</td>
</tr>
<tr>
<td>-----------------</td>
</tr>
<tr>
<td>Unit cost</td>
</tr>
</tbody>
</table>
Case Study

We implement the dynamic program formulated in Eq. (11) in Matlab 7.0. The results include total expected cost-to-go, suggested M&R policies, and the number of runways in operation, for each condition state combination and time period. Figs. 3-6 depict the total expected cost-to-go. To facilitate the comparison, each cost curve is drawn as a function of the time period for a constant condition state combination for the two runways (Figs. 3-6). As expected, the total expected cost-to-go declines continuously over time.

In addition, we observe prominent cost slope changes on some curves around the 22nd period, especially those involving the worst condition state. This relates to the choice of reconstruction. Fig. 7 illustrates the M&R actions taken for constant condition state combinations (1,4), (2,4), (3,4), and (4,4) throughout the planning horizon. From the beginning of the planning horizon until the 22nd period, reconstruction is regularly chosen if a runway stays in the worst condition state. By comparing the actual flight traffic on each runway with the runway capacities, we further find that reconstruction does not create any delays until the 8th period. During this period of time, reconstruction—like the other two M&R activities—does not impose any penalty in the total expected cost-to-go. After the 8th period, runway reconstruction, albeit more expensive because of both M&R and incurred delay costs, remains effective in minimizing total expected cost-to-go since it provides better runway conditions, reducing the subsequent user depreciation cost and

\footnote{Note that, given the symmetry of the two runways, condition states (1,4) and (4,1) represent the same situation. So are the other pairs.}
the need for reconstructing runways in latter periods where induced M&R delay cost would become more substantial. Starting in the 23rd period, due to continuous traffic growth, the M&R delay costs caused by runway reconstruction exceed the potential benefits in future periods; therefore, runway reconstruction is no longer part of the optimal policy. As only a subset of the M&R actions (maintenance and doing-nothing) is considered in the remaining time periods, we expect larger cost change between successive periods, resulting in a steeper slope.

Also associated with the reconstruction action are the zigzag areas which are, again, more apparent in the curves involving the worst condition state. Checking the optimal policies in Fig. 7, we observe that: 1) these zigzag areas corresponds to the time periods during which runway reconstruction is a feasible M&R policy; 2) within these periods reconstruction is only periodically selected. Recall the uneven seasonal distribution of traffic in a year (we assume slightly larger traffic volume in the 3rd and 4th quarters than the first two quarters). The optimal policy in a year will always choose the first two low-traffic quarters for runway reconstruction, whereas keeping both runways in operation in the remaining two quarters. This results in high depreciation cost in the latter two quarters (an exception is condition states (4,4), in which case depreciation cost in the current period remains unchanged). The worst condition state has further consequence on the ensuing periods, in which one has to either experience high depreciation cost (because runway conditions are not improved) or perform the expensive runway reconstruction, both adding to the expected cost-to-go at the current period. These explain the occurrence of peaks in Figs. 3-6.
Fig. 3. The evolution of total expected cost-to-go for condition states (1,1), (1,2), (1,3) and (1,4)

Fig. 4. The evolution of total expected cost-to-go for condition states (2,1), (2,2), (2,3) and (2,4)
Fig. 5. The evolution of total expected cost for condition states (3,1), (3,2), (3,3) and (3,4)

Fig. 6. The evolution of total expected cost for condition states (4,1), (4,2), (4,3) and (4,4)
To further explore the impact of M&R delays, we explicitly decompose the cost incurred in a given period, which we term “contemporary cost” for that period, into three components: delay cost, depreciation cost, and M&R action cost. Figs. 8 and 9 demonstrate the cost composition across all condition states in the 9th and 22nd periods—periods when M&R delay takes place for the first and last time respectively. In the 9th period, eight out of the sixteen condition state combinations require reconstruction to take place. These combinations are the ones with lower runway condition states. Delay cost is less than half the total contemporary cost, with M&R action cost accounting for another
major part. When both runways fall into the worst condition state, the depreciation cost rises substantially. Because reconstruction is much more expensive in terms of both M&R action and the associated delay cost than the other two M&R options, a cost disparity persists between condition states where reconstruction is selected and the remaining states. Such disparity is even more conspicuous in the 22\textsuperscript{nd} period, which results from more significant M&R delay costs due to traffic increase (Fig. 9). In effect, M&R delay cost becomes the largest component in the total. When at least one runway falls in the worst condition state, reconstruction is selected. In contrast, for condition state combinations where only maintenance or doing-nothing are selected in both periods, the contemporary cost changes between the two periods are small.

![Graph showing cost distribution](image)

**Fig. 8.** Contemporary cost under optimal policy in the 9\textsuperscript{th} period
Fig. 9. Contemporary cost under optimal policy in the 22nd period

Essentially, decisions on M&R actions when delay may be incurred reflect the trade-off between reconstruction and induced delay cost, and the benefits brought by significantly upgrading the pavement through reconstructing the runway. The benefits of better runway conditions are embodied in lower depreciation cost over the long run. To examine these benefits, we hypothetically rule out the option of reconstruction starting from the 9th period, the time when M&R delay first appears, and recalculate the total expected cost-to-go thereafter. This is to preclude any occurrence of M&R delays in the decision-making process. For each condition state combination, the new cost is compared to the one when reconstruction is included as a feasible M&R option. Results are shown in Fig. 10. Although the M&R delay cost can be large when it occurs, the long-term cost savings outweigh such delay cost, as represented by the difference between the two
curves. The long-term cost savings become increasingly prominent as the runway conditions get worse. The reason for reconstruction not being chosen after the 22\textsuperscript{nd} period can be interpreted by the same token: if reconstruction were performed in latter periods, the long-term cost savings from substantially improving runways conditions would not offset the associated M&R action and delay cost.

![Graph](image)

**Fig. 10.** Total expected cost-to-go with and without incurring M&R delays

**Sensitivity Analysis**

In this section we present a set of analyses to investigate the sensitivity of total costs to the values of several key parameters. The objective of some analyses is to examine how the optimal policy will change under different scenarios (for example, different demand levels). Other sensitivity analyses are motivated by the uncertainty in
some parameters. Examples include cost factors for depreciation and delay, and the parameter that represents the impact of traffic levels on transition probabilities.

**Demand**

Given the runway capacity, the total expected cost-to-go varies according to different demand levels, which are determined by the baseline demand and the growth rate. We first plot the total expected cost-to-go for condition states (1,1) in the 1\textsuperscript{st} planning period as a function of the baseline passenger demand. Fig. 11 reveals a positive relationship, and the increase in cost is substantial: almost tripled as the baseline demand increases from 6.5 million passengers to 10 million passengers per year. Similar conclusions can be drawn for other condition state combinations. Also displayed is the last reconstruction period, which can be seen to be very sensitive to baseline demand. For a given period, the higher the demand, the greater the M&R delay cost if it occurs. The optimal policy therefore tends to exclude reconstruction earlier in the planning horizon. In the cases where demand is extremely high, performing reconstruction becomes inferior to the other M&R options during the entire planning horizon.
Another factor that shapes demand is its growth rate. The curves describing total expected cost-to-go for condition states (1,1) and last reconstruction period are illustrated in Fig. 12, for an annual growth rate ranging from 0% to 4%. A sharper growth rate discourages runway reconstruction while increasing total expected cost-to-go. We observe that, except for very low demand growth rates for which the last reconstruction time is close to the end of the planning horizon, the slope of the last reconstruction period curve flattens with the increase in growth rate. This phenomenon could be attributed to the fact that demand growth is compromised more by the discounting factor in latter periods than in earlier ones.
Fig. 12. Effect of demand growth rate on total expected cost-to-go

(for condition states (1,1)) and the last period when reconstruction is chosen

**Depreciation Cost Factor**

Depreciation cost represents aircraft wear and tear, which are affected by pavement condition, for example, the unevenness or roughness of the runway surface. One manifestation is aircraft fatigue. However, the literature on the relation between roughness and cost is sketchy. Safety may present another consequence of poor pavement condition. The cost factor for condition state 4, albeit high in our assumption, may not be able to fully capture the safety concern. We therefore test the sensitivity of the total expected cost-to-go at the beginning of the planning horizon to a range of values for the worst condition state depreciation cost factor. Fig. 13 shows the results for four of the sixteen condition state combinations. As expected, the total expected cost-to-go increases with the depreciation cost factor, but at a diminishing rate. Using $5000/aircraft—the highest cost factor in our analysis range—we obtain a total expected cost-to-go about 1.4
times the cost using a depreciation cost factor of $500/aircraft. For the other twelve condition state combinations not shown here, similar conclusions can be drawn. As the penalty from operating under the worst condition state becomes greater, reconstruction remains in the optimal policy set for a longer period of time. The last reconstruction time increases—also at a diminishing rate—from the 22\textsuperscript{nd} to the 38\textsuperscript{th} period of time (Fig. 14). The significant cost increase may carry some policy implications. In the real world, due to safety concerns it is plausible for airport agencies or regulators to impose mandates to prevent pavements from falling into condition state 4. This in effect can be regarded as an extreme case where the user depreciation cost factor becomes infinitely high when operating under the worst condition state. The sensitivity analysis suggests that such mandates may force more frequent reconstructions throughout the planning horizon.

![Effect of user costs on total expected cost-to-go for condition states (1,1), (1,2), (1,3) and (1,4)](image)

**Fig. 13.** Effect of user costs on total expected cost-to-go
Delay Cost Factors

Uncertainty in parameter values arises in the delay-related cost factors as well. The study of GRA Inc. et al. (2004), based on which we determined the delay cost factors, is just one among numerous research efforts that have focused on estimating the unit delay cost for airlines and passengers (e.g. Ball et al., 2009). The vast number of such studies produced a wide range of possible delay factor values. Apart from data and methodological differences in the estimation, the discrepancy of cost factor values can stem from different fleet structures and operational efficiencies on the airline side, and market characteristics such as the trip purpose mix (i.e. business vs. leisure) on the passenger side. To account for these discrepancies, we vary both airline and passenger
cost factors by a range that covers the majority of existing values. The total expected costs-to-go at the beginning of the planning horizon for condition states (1,1) as a function of airline cost factors and passenger values of time are illustrated respectively in Figs. 15 and 16. For other condition state combinations, we observe very similar trends. Both curves in Figs. 15 and 16 follow an increasing trend, indicating a positive impact of delay cost factors on total expected cost-to-go. Furthermore, kinks that exist on each curve coincide with drops in the last reconstruction period, suggesting that the costlier the M&R delay, the more reluctant airport agencies should be to reconstruct runways. Overall, delay cost factors seem only to have limited cost effects. As shown in Figs. 15 and 16, the cost variation is marginal compared with the previous sensitivity cases. Recall that ground and airborne delays involve distinct unit delay cost ($1000 vs $4000 per hour). The results in Fig. 15 imply that the choice of ground or airborne delay is not important in M&R decision making, since this does not substantially alter the cost.

![Graph](image)

**Fig. 15.** Effect of airline cost factors on total expected cost-to-go for condition states (1,1)
Fig. 16. Effect of passenger value of time on total expected cost-to-go for condition states (1,1)

**Impact of Traffic Level on Transition Probabilities**

In setting the transition probabilities we introduce a parameter $\theta$ to capture the effect of different traffic levels on pavement deterioration. A larger value of $\theta$ implies a greater probability for the condition to drop to a worse condition state. This will result in a larger depreciation cost and motivate more expensive M&R actions in future planning periods. Fig. 17 confirms such a conjecture. Again, the total expected cost-to-go at the beginning of the planning horizon is plotted against a range of $\theta$ values, from 0 to 0.15, the maximum allowed in our transition probability matrices. For brevity only the curve for condition state combination (1,1) is shown, but it is representative of all condition states. We observe that the increase in cost is linear over the range of $\theta$ values, which
however does not affect the last reconstruction period. Magnitude wise, a considerable variation of the total expected cost-to-go over the feasible range of $\theta$ values suggests the importance of accurately capturing the impact of traffic levels on runway deterioration process.

![Figure 17](attachment:image.png)

**Fig. 17.** Effect of $\theta$ on total expected cost-to-go for condition states (1,1)

**Conclusion**

This paper develops a quantitative model that integrates several relevant elements in the airport runway pavement M&R planning process. It explicitly takes into consideration M&R action time, functional interdependence between runways, as well as traffic growth, and incorporates delay cost into the M&R decision-making process. The results obtained through the use of dynamic programming provide interesting insight into
the interplay among these elements. In the absence of M&R delays, reconstructing a runway brings greater benefits than other alternatives and is therefore frequently optimal. With an increase in traffic demand, however, these benefits have to be weighed against M&R delay cost. The decision to reconstruct a runway in the presence of potential M&R delays reflects the trade-off between present M&R action and delay cost, and the long-term benefits brought by significantly upgrading pavement conditions through reconstruction. When the former is offset by the latter, reconstructing one runway while incurring M&R delay is justified. Our sensitivity analyses reveal that the traffic demand has a strong influence on the expected cost-to-go as well as the choice of M&R actions. In addition, the parameter that represents the effect of traffic on the condition transition probabilities is seen to have an important effect on costs.

We suggest further work in several areas. First, this paper only considers two runways exclusively for landings. It should be interesting to extend this analysis to mixed operations. Second, refinement of the delay model presents another area, which may require more detailed characterization of the queueing process of flight arrivals. Third, given the model sensitivity to some of the parameter specifications, one could argue that our model might not be very useful even though it considers more factors than simpler models. The model, however, can be further enhanced with additional field data collection and more accurate estimation of model parameters. With all these, the advantages of the model presented in this study will eventually contribute to a better decision making process in airport runway pavement management.
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References


