Aviation Infrastructure Economics

October 14-15, 2004

The Aerospace Center Building
901 D St. SW, Suite 850
Washington, DC 20024
Lecture BWI/Andrews Conference Rooms

Instructor:
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Introduction to Optimization Techniques for Infrastructure Management

Application – Markov Decision Processes for Infrastructure Management, Maintenance and Rehabilitation

October 15, 2004

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Background

Relevant NAS Measures of Performance and their Relations

- Ideal Capacity
  - Capacity and Delay
  - Air Transport System Performance
  - Social and Economic Benefits of Aviation

- Income
  - Demand for Services
  - Structure of Production

- Reliability
  - Availability
  - Maintainability
Can the airspace users have extra benefits from our maintenance actions?

Cost Center Description:
- Staffing
- Sparring
- Probability distributions for equipment MTBF
- Type of failure
- Scheduled or unscheduled
- Travel Time
- Shift Policies
- Administrative Time
- Technician Qualifications

Service Description:
- Equipment making up a service
- Redundancy

Output Measures:
- Technician Utilization
- Outage Durations

Output measure:
- Availability

Module

Cost Center

Airport Characteristics:
- Aircraft mix
- Aircraft class
- Speed
- % weather (VFR and IFR)
- Final Approach Path Geometry
- Holding Pattern
- Number of runways
- Aircraft arrival demand
- Sequencing rule
- Mile-in-trail separation matrices
- Runway occupancy time

Output Measures:
- Capacity
- Aircraft delay
- Runway utilization
- Final approach path statistics
- Aircraft queue statistics

Airport Model
Models for
The National Airspace System
Infrastructure Performance and
Investment Analysis

October 15, 2004

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Constrained Optimization for Steady State Maintenance, Repair & Rehabilitation (MR&R) Policy

The objective is to apply constrained optimization model to solve an optimal steady state NAS infrastructure management problem, focusing on Terminal Airspace/Runway navigational equipment.

Markov Decision Process is reduced to a linear programming formulation to determine the optimum policy.
Review of Special Types of Linear Programming problems:

- transportation problem
- transshipment problem
- assignment problem

Review of Dynamic Programming (a mathematical technique often useful for making a sequence of interrelated decisions):

- deterministic
- probabilistic
Review of Inventory Theory:
- components
- deterministic models
- stochastic models

Review of Markov Decision Processes:
- Markov decision models
- linear programming and optimal policies
- policy-improvement algorithms for finding optimal policies
### Methodology

**Markov Decision Processes**

<table>
<thead>
<tr>
<th>Decision</th>
<th>Cost</th>
<th>Expected cost due to caused traffic delays Cd</th>
<th>Maintenance Cost Cm</th>
<th>Total Cost Ct = Cd + Cm</th>
</tr>
</thead>
</table>
| 1. Leave ASR as it is | 0 = good as new  
1 = operable – minor deterioration  
2 = operable – major deterioration  
3 = inoperable | $0  
$1,000,000 (for example)  
$6,000,000  
$20,000,000 | $0  
$0  
$0 | $0  
$1,000,000  
$6,000,000  
$20,000,000 |
| 2. Maintenance    | 0 = good as new  
1 = operable – minor deterioration  
2 = operable – major deterioration  
3 = inoperable | If scheduled, $0; otherwise $X2  
If scheduled, $0; otherwise $Y2  
If scheduled, $0; otherwise $Z1  
If scheduled, $M2; otherwise $N2 | If scheduled $A2, otherwise $B2  
If scheduled $C2, otherwise $D2  
If scheduled $E2, otherwise $F2  
If scheduled $G2, otherwise $H2 | Cd + Cm |
| 3. Replace        | 0 = good as new  
1 = operable – minor deterioration  
2 = operable – major deterioration  
3 = inoperable | If scheduled, $0; otherwise $X3  
If scheduled, $0; otherwise $Y3  
If scheduled, $0; otherwise $Z3  
If scheduled, $M3; otherwise $N3 | If scheduled $A3, otherwise $B3  
If scheduled $C3, otherwise $D3  
If scheduled $E3, otherwise $F3  
If scheduled $G3, otherwise $H3 | Cd + Cm |
| 4. Upgrade        | 0 = good as new  
1 = operable – minor deterioration  
2 = operable – major deterioration  
3 = inoperable | If scheduled, $0; otherwise $X4  
If scheduled, $0; otherwise $Y4  
If scheduled, $0; otherwise $Z4  
If scheduled, $M4; otherwise $N4 | If scheduled $A4, otherwise $B4  
If scheduled $C4, otherwise $D4  
If scheduled $E4, otherwise $F4  
If scheduled $G4, otherwise $H4 | Cd + Cm |
Methodology

Markov Decision Processes

Markov Decision Processes studies sequential optimization of discrete time random systems. The basic object is a discrete-time random system whose transition mechanism can be controlled over time.

Each control policy defines the random process and values of objective functions associated with this process. The goal is to select a “good” control policy.
Methodology

Markov Decision Processes

<table>
<thead>
<tr>
<th>Interrupt Condition</th>
<th>Entry Type</th>
<th>Code Cause</th>
</tr>
</thead>
<tbody>
<tr>
<td>FL Full outage</td>
<td>LIR Log Interrupt condition</td>
<td>60 Scheduled Periodic Maintenance</td>
</tr>
<tr>
<td>RS Reduced Service</td>
<td>LCM Log Corrective Maintenance</td>
<td>61 Scheduled Commercial Lines</td>
</tr>
<tr>
<td>RE Like Reduced Service but no longer used</td>
<td>LPM Log Preventative Maintenance</td>
<td>62 Scheduled Improvements</td>
</tr>
<tr>
<td></td>
<td>LEM Log Equipment Upgrade Logs</td>
<td>63 Scheduled Flight Inspection</td>
</tr>
<tr>
<td></td>
<td></td>
<td>64 Scheduled Administrative</td>
</tr>
<tr>
<td></td>
<td></td>
<td>65 Scheduled Corrective Maintenance</td>
</tr>
<tr>
<td></td>
<td></td>
<td>66 Scheduled Periodic Software Maintenance</td>
</tr>
<tr>
<td></td>
<td></td>
<td>67 Scheduled Corrective Software Maintenance</td>
</tr>
<tr>
<td></td>
<td></td>
<td>68 Scheduled Related Outage</td>
</tr>
<tr>
<td></td>
<td></td>
<td>69 Scheduled Other</td>
</tr>
<tr>
<td></td>
<td></td>
<td>80 Unscheduled Periodic Maintenance</td>
</tr>
<tr>
<td></td>
<td></td>
<td>81 Unscheduled Commercial Lines</td>
</tr>
<tr>
<td></td>
<td></td>
<td>82 Unscheduled Prime Power</td>
</tr>
<tr>
<td></td>
<td></td>
<td>83 Unscheduled Standby Power</td>
</tr>
<tr>
<td></td>
<td></td>
<td>84 Unscheduled Interface Condition</td>
</tr>
<tr>
<td></td>
<td></td>
<td>85 Unscheduled Weather Effects</td>
</tr>
<tr>
<td></td>
<td></td>
<td>86 Unscheduled Software</td>
</tr>
<tr>
<td></td>
<td></td>
<td>87 Unscheduled Unknown</td>
</tr>
<tr>
<td></td>
<td></td>
<td>88 Unscheduled Related Outage</td>
</tr>
<tr>
<td></td>
<td></td>
<td>89 Unscheduled Other</td>
</tr>
</tbody>
</table>
Markov Decision Process

Linear Programming and Optimal Policies

General Formulation

\[ C_{ik} \]
Expected cost incurred during next transition if system is in state \( i \) and decision \( k \) is made

\[ y_{ik} \]
Steady state unconditional probability that the system is in state \( i \) AND decision \( k \) is made

\[ y_{ik} = P\{\text{state} = i \text{ and decision} = k\} \]
Markov Decision Process
Linear Programming and Optimal Policies

General Formulation

OF

Min \sum_{i=0}^{M} \sum_{k=1}^{K} C_{ik} y_{ik}

subject to the constraints

(1) \sum_{i=0}^{M} \sum_{k=1}^{K} y_{ik} = 1

(2) \sum_{k=1}^{K} y_{jk} - \sum_{i=0}^{M} \sum_{k=1}^{K} y_{ik} p_{ij}(k) = 0 \quad , \quad \text{for } j = 0,1,...,M

(3) y_{ik} \geq 0 \quad , \quad i = 0,1,...,M; \quad k = 1,2,......,K
Conditional probability that the decision $k$ is made, given the system is in state $i$:

$$D_{ik} = P\{\text{decision} = k \mid \text{state} = i\}$$
Assumptions

- network-level problem

*non-homogeneous network* (contribution)

Dynamic Programming (DP) used for single facility problems

Linear Programming (LP) used for network-level problems
Markov Decision Process

Linear Programming and Optimal Policies

Assumptions

• deterioration process
  - constant over the planning horizon

• inspections
  - reveal true condition
  - performed at the beginning of every year for all facilities
Transition Probability Matrix

\[ P(k|li,a) \] is an element in the matrix which gives the probability of equipment \( j \) being in state \( k \) in the next year, given that it is in the state \( i \) in the current year when action \( a \) is taken.
Specific Problem

Data:

Note: 

$i$ is a condition

$j$ is an equipment

$a$ is an action

The cost $C_{iaj}$ of equipment $j$ in condition $i$ when action $a$ is employed.

The user cost $U$ is calculated from the overall condition of the airport.

$Budget_j$ The budget for equipment $j$
Decision Variable:

\( W_{iaj} \) Fraction of equipment \( j \) in condition \( i \) when action \( a \) is taken.

Note that some types of equipment have only one or two items per type of equipment. Therefore, some \( W_{iaj} \) are equal to 1.
Specific Problem

Objective Function:

Minimize the total cost per year (long term):

\[
\text{Minimize } \sum_i \sum_a \sum_j [C(i, a, j)] \times W_{iaj} + U(f(A, \eta, \text{pax-cost}))
\]
Constraint (1): mass conservation constraint
In order to make sure that the mass conservation holds, the sum of all fractions has to be 1.

\[ \sum_i \sum_a W_{iaj} = 1 \quad \forall j \]
Specific Problem

$C_{iaj}$:
Cost of equipment $j$ in condition $i$ when action $a$ is employed.

$U$ cost:
$A$ airport service availability

$\eta$ passenger load (per aircraft)

pax-cost

$$\sum\sum\sum \left[ C(i, a, j) \right] \times W_{iaj} + U \left( f(A, \eta, \text{pax-cost}) \right)$$
Specific Problem

Constraint (2): All fractions are greater than 0

\[ W_{ia} \geq 0 \quad \forall a, \forall i \]

Constraint (3): Steady-state constraint is added to verify that the Chapman-Kolmogorov equation holds.

\[ \sum_{i} \sum_{a} W_{iaj} \ast P_{j}(k \mid i, a) = \sum_{a} W_{kaj} \quad \forall j \]
Constraint (4): This constraint is added to make sure that there will be less than 0.1 in the worst state.

\[ \sum_{a} W_{3aj} < 0.1 \]

Constraint (5): This constraint is added to make sure that there will be more than 0.3 in the best state.

\[ \sum_{a} W_{1aj} > 0.3 \]
Specific Problem

Constraint (6): Non-negativity constraint

\[ C(i, a, j) \geq 0 \quad \forall i, a \]

Constraint (7): Budget constraint

\[ \sum_{i} \sum_{a} C(i, a, j) \times W_{iaj} \leq \text{Budget}_j \quad \forall j \]
Additional assumptions:

1) All pieces of equipment are independent. This assumption allows the steady-state constraint to be considered independently; that is, the probability of the next year condition depends only on the action taken on that equipment only.

2) During the scheduled maintenance, it is assumed that the equipment is still working properly although it is actually turned off. This assumption is based on the fact that before any scheduled maintenance, there is a preparation or a back-up provided in order to maintain the same level of service.

3) We assume the VFR condition is 70% of the total operating time; and IFR CATI, II, III are 10% of the total operating time, respectively.
The time period in the probability matrix is 1 year. Unscheduled maintenance actions (outages, cause code 80-89) represent the condition $i$ of an equipment piece.

The scheduled maintenance actions (code 60-69) represent an action $a$ taken in each year.

Given the total time of outages and scheduled maintenances from the historical data, obtained are transitional probability matrices.
Methodology

NAPRS historical data:
- Cause code 60 to identify actions
- Cause code 80 to identify conditions

Obtain transition probability matrix

Maintenance cost for all actions

OBJECTIVE FUNCTION

User cost as a function of delay

Maintenance cost

Fault Tree analysis to identify availability of runways — used to measure delay

Optimal policy: Minimizes the objective function
Numerical Example

- Single airport with 1 runway.
- During IFR conditions, an arriving runway requires 7 types of equipment. If assumed that all types of equipment have the same transition probability matrix, all pieces of equipment are homogeneous. Otherwise, they are non-homogeneous.
- Airport is under IFR conditions 30% of the time. Half of the time is used for departures and the other half is utilized by arrivals.
Numerical Example

- We define conditions and actions as follows:
  - action 1: maintenance actions have low frequency
  - action 2: maintenance actions have medium frequency
  - action 3: maintenance actions have high frequency
  - condition 1: availability is less than 99%
  - condition 2: availability is 99%-99.5%
  - condition 3: availability is 99.5%-100%

- The maintenance cost varies by actions and conditions taken.
## Assumptions

<table>
<thead>
<tr>
<th>Maintenance cost ($/hr)</th>
<th>action 1</th>
<th>action 2</th>
<th>action 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>condition 1</td>
<td>1000</td>
<td>1500</td>
<td>2000</td>
</tr>
<tr>
<td>condition 2</td>
<td>800</td>
<td>1200</td>
<td>1500</td>
</tr>
<tr>
<td>condition 3</td>
<td>600</td>
<td>900</td>
<td>1000</td>
</tr>
</tbody>
</table>
Numerical Example

- The availability of the runway is calculated from the fault tree. Fault trees for arrivals and departures are different.

- To calculate the user cost, we use the availability for each condition state to calculate the expected downtime/year (the period that the airport can’t operate due to outages). Then, we use the average load factor multiplied by the average passenger/plane and by the average plane/hour to find the total lost time for all passengers. Then, we use the value $28.6/hour as a value of time for each passenger.
Numerical Example

- Each piece of equipment affects airport performance differently, depending on the visibility, wind conditions, noise constraints, primary runway configuration in use and ATC procedures.

- Consequences of equipment outages are also airport specific.
Numerical Example

Top Level Category III IFR Arrival Failure Fault Tree
Numerical Example

We vary our budget in the budget constraint for maintenance costs. Then, we perform the sensitivity analysis.
Assume: budget = $250000/year

<table>
<thead>
<tr>
<th>$W_{iaj}$</th>
<th>action</th>
</tr>
</thead>
<tbody>
<tr>
<td>condition</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
</tr>
</tbody>
</table>

Total cost is $W_{iaj} \times C_{iaj} + U = 210000 + 0 = $210000/year
Assume: budget = $200000/year

<table>
<thead>
<tr>
<th>$W_{iaj}$</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>condition</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>0.101378</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
</tr>
</tbody>
</table>

Total cost is = 196516.8 + 126875.4 = $323392.2/year