Models for
The National Airspace System
Infrastructure Performance and
Investment Analysis

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What is a System?

“A system may be considered as constituting a nucleus of elements combined in such a manner as to accomplish a function in response to an identified need…A system must have a functional purpose, may include a mix of products and processes, and may be contained within some form of hierarchy…”

What is the National Airspace System?

“The common network of U.S. airspace; air navigation facilities, equipment and services, airports or landing areas; aeronautical charts, information and services; rules, regulations and procedures, technical information, and manpower and material. Included are system components shared jointly with the military.”

Pilot/Controller Glossary
NAS has about 48,000 reportable facilities and services that provide air traffic management (ATM) services.

NAS’ large inventory capital assets are in various stages of approaching physical or technical obsolescence.
Background

NAS is:

- highly technical
- highly integrated
- large and complex
Background

Relevant NAS Measures of Performance and their Relations

Reliability → Availability

Maintainability → Availability → Capacity and Delay
Objectives and Scope

- Identify and define factors that affect airport and terminal area availability and develop a methodology for airport/airspace availability.

- Develop a methodology for the analysis of the NAS infrastructure performance and investments.

- The methodology should assist the FAA to better evaluate airport and airspace performance considering infrastructure quality, redundancy, and life cycles.
Availability Modeling for Airports

Traditional availability estimates consider weather and equipment availability separately.

Equipment Availability: \( A = \frac{MTBF}{(MTBF + MTTR)} \)

\[ A_{op} = \frac{(t_s - t_{down})}{t_s} \]

Weather Availability: \( A_w = \frac{MTBC}{MTBC + MTTC_w} \)
Availability Modeling for Airports

However, during bad weather conditions airport availability for arrivals is different from the availability for departures due to different ceiling and visibility requirements.

Airport equipage influences weather availability: if an airport is not CAT III equipped, weather related availability is lower.

Relation between Weather Availability for Arrivals and Equipment Availability for CAT III Approaches
Airport arrival service availability and departure service availability:
includes weather and equipment availability
for each primary wind direction and noise constraint.
It is a percentage of time that a service for arrivals and departures is being provided.
Conceptual approach for airport service availability:

1) arrival and departure equipment availability estimated separately for each weather condition (VFR, IFR CAT I, CAT II and CAT III) using Fault Tree Analysis (FTA)

2) single runway availability is combined with that of other runways used within a particular runway configuration.

3) arrival and departure availability for each runway configuration used for service availability
Conceptual approach for availability estimation:

1) arrival and departure equipment availability estimated separately for each weather condition
   (VFR, IFR CAT I, CAT II and CAT III) using Fault Tree Analysis (FTA) Method

Boolean algebraic equations:

- Unavailability \( C \):
  \[ C = L + G + (N \times E) + (N \times V) + D + R + L \]
The runway availability for arrivals $a$ on runway $r$ in configuration $f$ (for a primary wind direction $w$ and noise constraint $n$) $A_{wnfr}^a$ is:

$$A_{wnfr}^a = \sum_{c=1}^{n} x_c A_{cr}^a$$

$A_{cr}^a$: arrival availability for weather category $c$, for runway $r$

$x_c$: percentage of time weather category $c$ is use

$C$: weather category
2) single runway availability is combined with that of other runways used within a particular runway configuration.

\[ A_{wnf}^{\alpha} = 1 - (1 - A_{wnfr}^{a}) \text{ single runway availability} \]

\[ A_{wnf}^{\alpha} = 1 - (1 - A_{wnfr_1}^{a})(1 - A_{wnfr_2}^{a})\ldots(1 - A_{wnfr_n}^{a}), \quad \text{for } r_i = r_1 \ldots r_n \]

where \( n \) is the number of runways
<table>
<thead>
<tr>
<th>Primary wind direction</th>
<th>Noise Constraint</th>
<th>Runway configuration</th>
<th>Primary Runways in Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>$w_1 = \text{North}$</td>
<td>None</td>
<td>$f_1$</td>
<td>Runways: 31R and 36R</td>
</tr>
<tr>
<td>$w_2 = \text{South}$</td>
<td>None</td>
<td>$f_1$</td>
<td>Runways: 13R, 17L</td>
</tr>
<tr>
<td>$w_2 = \text{South}$</td>
<td>None</td>
<td>$f_2$</td>
<td>Runways: 13R, 17C and 18R</td>
</tr>
</tbody>
</table>
3) arrival availability for each runway configuration used for service availability

The total airport arrival service availability $A^\alpha$ is weighted by the percentage of use of each previously calculated availability.

$$A^\alpha = \sum_{w=1}^{W} \sum_{n=1}^{N} \sum_{f=1}^{F} y_{wnf} A_{wnf}$$

- $W$: number of primary wind directions
- $N$: number of noise constraints
- $F$: number of runway configurations
- $y_{wnf}$: percentage of time each runway configuration $f$ was in use in primary wind direction $w$ and noise constraint $n$
Airport Availability Estimates
Case Study: Newark International Airport (EWR)

EWR
Runway Geometry
Required Data

EWR Runway IFR Capability

Runway Configuration Information

Outages by NAPRS Cause Code

Total Downtime by NAPRS Cause Code

Runway Configuration Information

Percent Occurrence of Weather Categories by Month, Daytime Hours
QRAS Software
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Availability</th>
</tr>
</thead>
<tbody>
<tr>
<td>A_A</td>
<td>Airport Arrival Availability</td>
<td>0.9950</td>
</tr>
<tr>
<td>A_D</td>
<td>Airport Departure Availability</td>
<td>0.9946</td>
</tr>
<tr>
<td>A_AC1</td>
<td>Arrival Availability for Configuration 1</td>
<td>0.9982</td>
</tr>
<tr>
<td>A_DC1</td>
<td>Departure Availability for Configuration 1</td>
<td>0.9931</td>
</tr>
<tr>
<td>A_AC2</td>
<td>Arrival Availability for Configuration 2</td>
<td>0.9573</td>
</tr>
<tr>
<td>A_DC2</td>
<td>Departure Availability for Configuration 2</td>
<td>0.9931</td>
</tr>
<tr>
<td>A_AC3</td>
<td>Arrival Availability for Configuration 3</td>
<td>1.0000</td>
</tr>
<tr>
<td>A_DC3</td>
<td>Departure Availability for Configuration 3</td>
<td>0.9965</td>
</tr>
<tr>
<td>A_AC4</td>
<td>Arrival Availability for Configuration 4</td>
<td>0.9989</td>
</tr>
<tr>
<td>A_DC4</td>
<td>Departure Availability for Configuration 4</td>
<td>0.9965</td>
</tr>
</tbody>
</table>

**Arrival and Departure Configuration Availabilities**
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Availability</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{AR4L}$</td>
<td>Arrival Availability, Runway 4L</td>
<td>0.9573</td>
</tr>
<tr>
<td>$A_{DR4L}$</td>
<td>Departure Availability, Runway 4L</td>
<td>0.9580</td>
</tr>
<tr>
<td>$A_{AR4R}$</td>
<td>Arrival Availability, Runway 4R</td>
<td>0.9989</td>
</tr>
<tr>
<td>$A_{DR4R}$</td>
<td>Departure Availability, Runway 4R</td>
<td>1.0000</td>
</tr>
<tr>
<td>$A_{AR11}$</td>
<td>Arrival Availability, Runway 11</td>
<td>0.9573</td>
</tr>
<tr>
<td>$A_{DR11}$</td>
<td>Departure Availability, Runway 11</td>
<td>0.9580</td>
</tr>
<tr>
<td>$A_{AR22L}$</td>
<td>Arrival Availability, Runway 22L</td>
<td>0.9573</td>
</tr>
<tr>
<td>$A_{DR22L}$</td>
<td>Departure Availability, Runway 22L</td>
<td>0.9580</td>
</tr>
<tr>
<td>$A_{AR22R}$</td>
<td>Arrival Availability, Runway 22R</td>
<td>0.9170</td>
</tr>
<tr>
<td>$A_{DR22R}$</td>
<td>Departure Availability, Runway 22R</td>
<td>0.9170</td>
</tr>
<tr>
<td>$A_{AR29}$</td>
<td>Arrival Availability, Runway 29R</td>
<td>0.9170</td>
</tr>
<tr>
<td>$A_{DR29}$</td>
<td>Departure Availability, Runway 29R</td>
<td>0.9170</td>
</tr>
</tbody>
</table>

Arrival and Departure Configuration Availabilities
Availability Improvements with IFR Equipment Upgrades

1. Upgrading runways 22R and 29 from a maximum capability of VFR to CAT I
2. Upgrading runways 4L, 11 and 22L from a maximum capability of CAT I to CAT II
3. Combining upgrades 1 and 2
Relevant NAS Measures of Performance and their Relations

- Reliability
- Availability
- Maintainability
- Capacity and Delay
Constrained Optimization for Steady State Maintenance, Repair & Rehabilitation (MR&R) Policy

The objective of this part of research 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.
### Methodology

#### Markov Decision Processes

<table>
<thead>
<tr>
<th>Decision</th>
<th>Cost</th>
<th>Expected cost due to caused traffic delays</th>
<th>Maintenance Cost</th>
<th>Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>State (probability)</td>
<td></td>
<td></td>
<td>Ct = Cd + Cm</td>
</tr>
<tr>
<td>1. Leave ASR as it is</td>
<td>0 = good as new</td>
<td>$0</td>
<td>$0</td>
<td>$0</td>
</tr>
<tr>
<td></td>
<td>1 = operable – minor deterioration</td>
<td>$1,000,000 (for example)</td>
<td>$0</td>
<td>$1,000,000</td>
</tr>
<tr>
<td></td>
<td>2 = operable – major deterioration</td>
<td>$6,000,000</td>
<td>$0</td>
<td>$6,000,000</td>
</tr>
<tr>
<td></td>
<td>3 = inoperable</td>
<td>$20,000,000</td>
<td>$0</td>
<td>$20,000,000</td>
</tr>
<tr>
<td>2. Maintenance</td>
<td>0 = good as new</td>
<td>If scheduled, $0; otherwise $X2</td>
<td>If scheduled $A2, otherwise $B2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1 = operable – minor deterioration</td>
<td>If scheduled, $0; otherwise $Y2</td>
<td>If scheduled $C2, otherwise $D2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2 = operable – major deterioration</td>
<td>If scheduled, $0; otherwise $Z1</td>
<td>If scheduled $E2, otherwise $F2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3 = inoperable</td>
<td>If scheduled, $M2; otherwise $N2</td>
<td>If scheduled $G2, otherwise $H2</td>
<td></td>
</tr>
<tr>
<td>3. Replace</td>
<td>0 = good as new</td>
<td>If scheduled, $0; otherwise $X3</td>
<td>If scheduled $A3, otherwise $B3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1 = operable – minor deterioration</td>
<td>If scheduled, $0; otherwise $Y3</td>
<td>If scheduled $C3, otherwise $D3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2 = operable – major deterioration</td>
<td>If scheduled, $0; otherwise $Z3</td>
<td>If scheduled $E3, otherwise $F3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3 = inoperable</td>
<td>If scheduled, $M3; otherwise $N3</td>
<td>If scheduled $G3, otherwise $H3</td>
<td></td>
</tr>
<tr>
<td>4. Upgrade</td>
<td>0 = good as new</td>
<td>If scheduled, $0; otherwise $X4</td>
<td>If scheduled $A4, otherwise $B4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1 = operable – minor deterioration</td>
<td>If scheduled, $0; otherwise $Y4</td>
<td>If scheduled $C4, otherwise $D4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2 = operable – major deterioration</td>
<td>If scheduled, $0; otherwise $Z4</td>
<td>If scheduled $E4, otherwise $F4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3 = inoperable</td>
<td>If scheduled, $M4; otherwise $N4</td>
<td>If scheduled $G4, otherwise $H4</td>
<td></td>
</tr>
</tbody>
</table>
## 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</td>
<td>LPM Log Preventative Maintenance</td>
<td>62 Scheduled Improvements</td>
</tr>
<tr>
<td>but no longer used</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
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

$P(k|i,a)$ 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.
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 equipments have only one or two items per type of equipment. Therefore, we set some $W_{iaj}$ equal to 1.
Objective Function:
Minimize the total cost per year (long term)

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

Constraint (1): mass conservation constraint
In order to make sure that the mass conservation hold, the sum of all fractions has to be 1.

\[ \sum \sum W_{iaj} = 1 \quad \forall j \]
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.

\[ \sum_i \sum_a W_{iaj} * P_j(k \mid i, a) = \sum_a W_{kaj} \quad \forall j \]
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.

\[ \sum_{a} W_{1aj} > 0.3 \]
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 CAT I, II, III are 10% of the total operating time, each.
Methodology

For the calculation based on historical data, the problem formulated in AMPL.

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.
Numerical Example

- Single airport with 1 runway.

- With 1 runway during IFR condition, it 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

Runway Service Alternatives

WEATHER
- good
- bad

EQUIPMENT
- up
- down

ALTERNATIVE ATC PROCEDURES
- no
- not required
- no
- yes
- not required

RUNWAY SERVICE
- up
- OUT
- up
- OUT
- up
- up
- up

CASE
- A
- B
- C
- D
- E
- F
- G
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></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
**Numerical Example**

**Maintenance Management System (MMS) Data**
- Data:
  1. arrival throughput per 15 minutes
  2. departure throughput per 15 minutes
  3. flight rule: VFR or IFR
  4. visibility
  5. ceiling
  6. wind speed

**Aviation System Performance Matrics (ASPM) DATA**
- Data:
  1. equipment name
  2. equipment type
  3. outage start time and date
  4. outage end time and date
  5. interrupt condition code
  6. entry type code
  7. outage cause code

**Tobit Model:**

- Arr$_t$ = \[ \begin{align*}
  & \text{Capacity} = \beta_{0t} + \sum_{n=1}^{N} \beta_{nt} x_{nt} + \varepsilon_t, \text{ if } \beta_{0t} + \sum_{n=1}^{N} \beta_{nt} x_{nt} + \varepsilon_t < \text{Demand}, \\
  & \text{otherwise}
\end{align*} \]

- Dep$_t$ = \[ \begin{align*}
  & \text{Capacity} = \beta_{0t} + \sum_{n=1}^{N} \beta_{nt} x_{nt} + \varepsilon_t, \text{ if } \beta_{0t} + \sum_{n=1}^{N} \beta_{nt} x_{nt} + \varepsilon_t < \text{Demand}, \\
  & \text{otherwise}
\end{align*} \]

**Methodology for Aircraft Throughput during Outages**
Numerical Example

\[ Arr_t \] arrival throughput in time interval, which is usually 15 minutes;

\[ \beta_{0t} \] constant to be estimated in the model in time interval;

\[ \beta_{nt} \] \( n \)th coefficients to be estimated in time interval;

\[ x_{nt} \] \( n \)th independent variable in time interval;

\[ \varepsilon_t \] error term of the model in time interval;

\[ Capacity_t \] capacity in time interval;

\[ Demand_t \] demand in time interval.

Methodology for Aircraft Throughput during Outages
# List of VOR Short Unscheduled Outages at SFO

<table>
<thead>
<tr>
<th>Facility Type</th>
<th>Code Category</th>
<th>Interrupt Condition</th>
<th>Outage Local Start Date and Time</th>
<th>Outage Local End Date and Time</th>
</tr>
</thead>
<tbody>
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<td>VOR</td>
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<td>7/9/02 16:44</td>
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</table>
### Analysis Results for ALSF-2s

<table>
<thead>
<tr>
<th>Runway Configuration (arrivals</th>
<th>departures)</th>
<th>Weather Condition (IFR of VFR)</th>
<th>Time Interval (local)</th>
<th>Dummy Variable</th>
<th>Estimated Affect on Throughput **</th>
<th>t-value</th>
<th>Significance at 0.05 Level</th>
<th>Number of Observations ***</th>
</tr>
</thead>
<tbody>
<tr>
<td>28L, 28R</td>
<td>VFR</td>
<td>18:00 pm-22:00 pm</td>
<td>Outage* (occurred)</td>
<td>0.2904</td>
<td>0.30</td>
<td>0.7628 (not significant)</td>
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<tr>
<td>1L, 1R</td>
<td>VFR</td>
<td>18:00 pm-22:00 pm</td>
<td>Outage</td>
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<td>1.16</td>
<td>0.2452 (not significant)</td>
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<td>18:00 pm-22:00 pm</td>
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<td>0.00</td>
<td>0.9999 (not significant)</td>
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<td>1L, 1R</td>
<td>IFR</td>
<td>18:00 pm-22:00 pm</td>
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<td>-0.92</td>
<td>0.3590 (not significant)</td>
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</tbody>
</table>

* Outage = 1 if there was an ALSF-2 outage during the period j; otherwise Outage = 0.
** Estimated change in quarter-hour throughput.
*** Each observation is 1 quarter-hour period.
Consequences of equipment outages are very much airport specific.

SFO is not sensitive to VOR unscheduled outages during IFR and VFR conditions.

ALSF-2 unscheduled outages during the IFR Conditions do not cause capacity degradation.
Research Extensions:

- Analysis of the bathtub curve for determining the optimum timing to replace aging pieces of equipment.