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…"

Logistics Engineering and Management, 5th Edition, Benjamin S. Blanchard, Prentice Hall Inc., 1998.

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

Background

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.

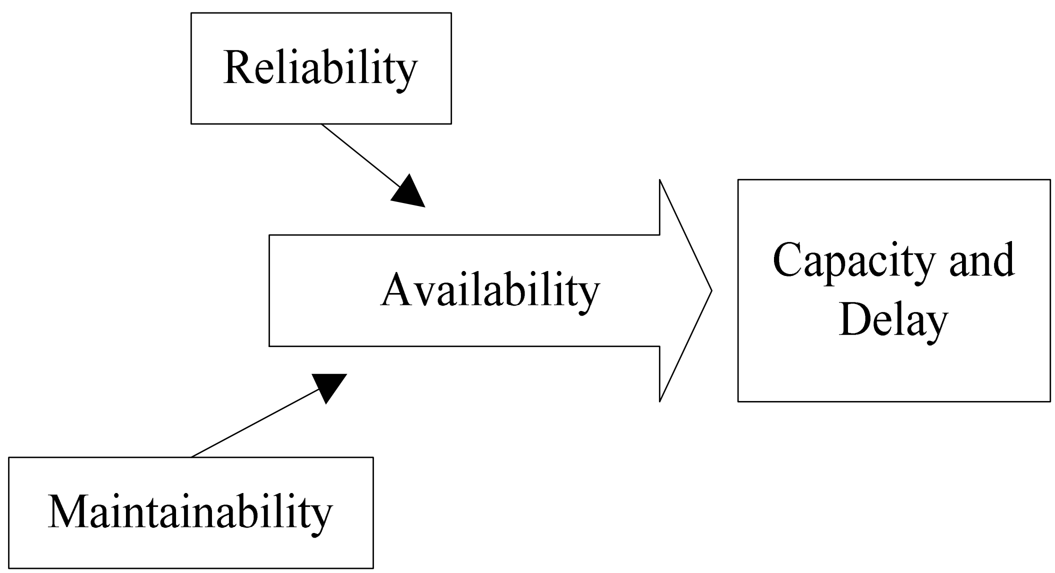
Background

NAS is:

- highly technical
- highly integrated
- large and complex

Background

Relevant NAS Measures of Performance and their Relations



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: $A = MTBF / (MTBF + MTTR)$

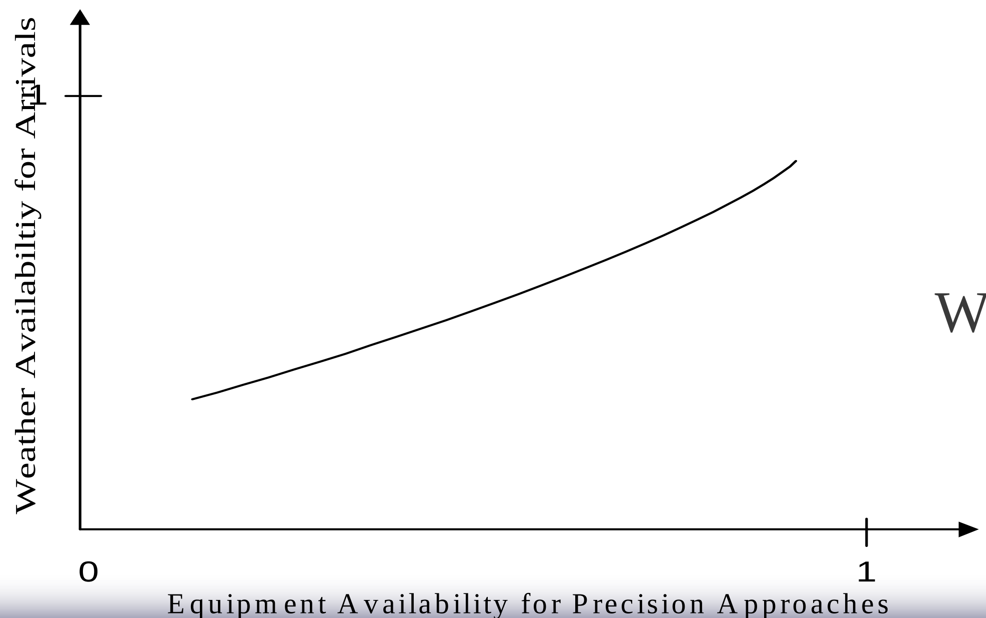
$$A_{op} = (t_s - t_{down}) / t_s$$

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.

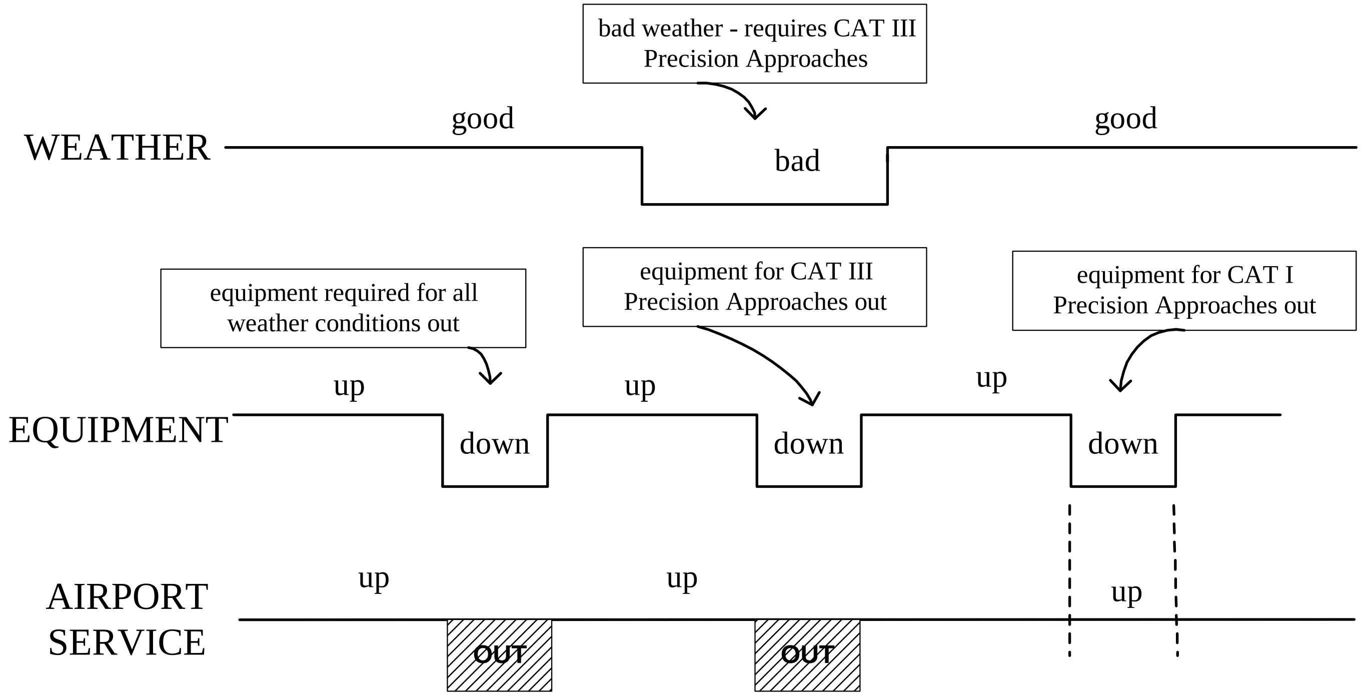


Relation between Weather Availability for Arrivals and Equipment Availability for CAT III Approaches

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.



Arrival Service Availability

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.

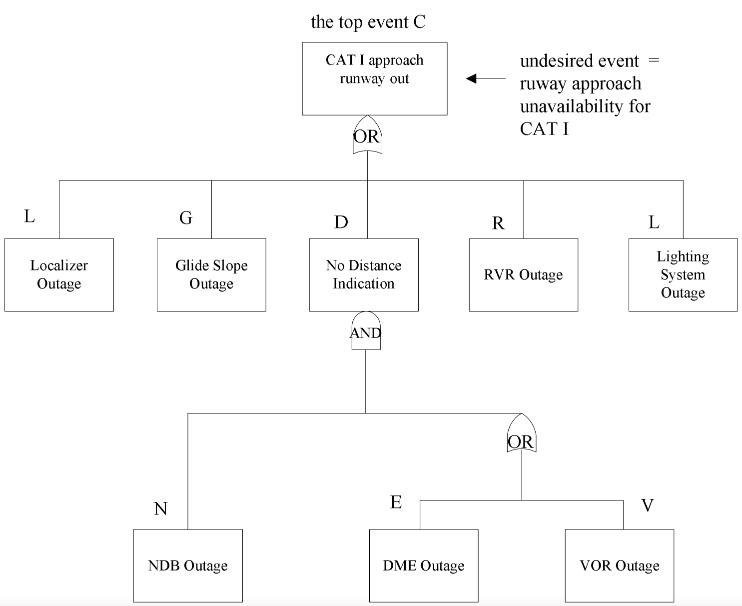
3) arrival and departure availability for each runway configuration used for service availability

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:

C = L + G + D + R + L

D = N x (E + V)

Unavailability C:

C = L + G + (N x E) + (N x 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^a_{wnfr} is:

$$A^a_{wnfr} = \sum_{c=1}^{n} x_c A^a_{cr}$$

A^a_{cr} : arrival availability for weather category *c*, for runway *r*

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

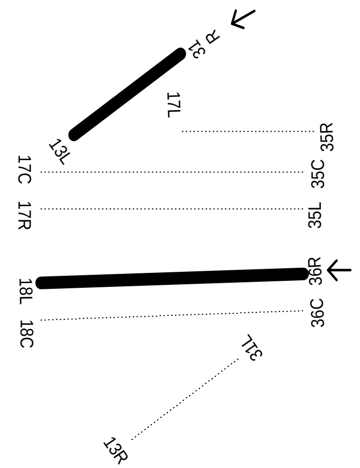
C : weather category

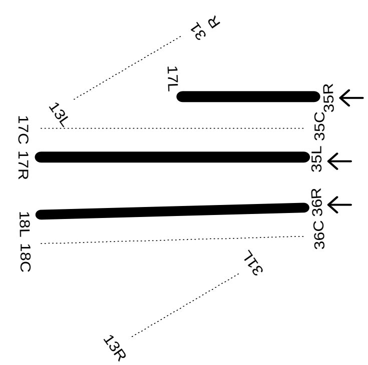
2) single runway availability is combined with that of other runways used within a particular runway configuration.

$$A^{\alpha}_{wnf} = 1 - (1 - A^{a}_{wnfr}) \quad \text{single runway availability}$$

$$A^{\alpha}_{wnf} = 1 - (1 - A^{a}_{wnfr_1})(1 - A^{a}_{wnfr_2}).....(1 - A^{a}_{wnfr_n}), \quad \text{for } r_i = r_1 .... r_n$$

where n is the number of runways

<table>
<tr><th>Primary wind direction
w</th><th>Noise Constraint
N</th><th>Runway configuration
f</th><th>Primary Runways in Use
R</th></tr>
<tr><td>w_1 = North</td><td>None</td><td>f_1</td><td>

runways: 31R and 36R</td></tr>
<tr><td>w_1 = North</td><td>None</td><td>f_2</td><td>

runways: 35R, 35L, and 36R</td></tr>
<tr><td>w_1 = North</td><td>None</td><td>f_3</td><td>Runways: 35C and 36C</td></tr>
<tr><td>w_2 = South</td><td>None</td><td>f_1</td><td>Runways: 13R, 17L</td></tr>
<tr><td>w_2 = South</td><td>None</td><td>f_2</td><td>Runways: 13R, 17C and 18R</td></tr>
</table>

3) arrival availability for each runway configuration used for service availability

The total airport arrival service availability A^{α} is weighted by the percentage of use of each previously calculated availability.

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

W : number of primary wind directions

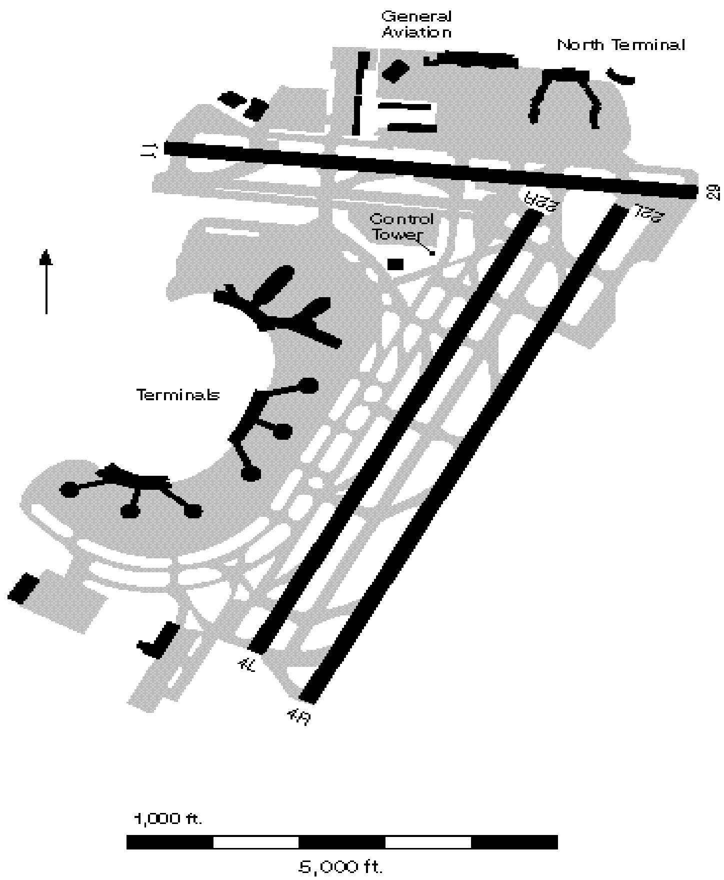
N : number of noise constraints

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

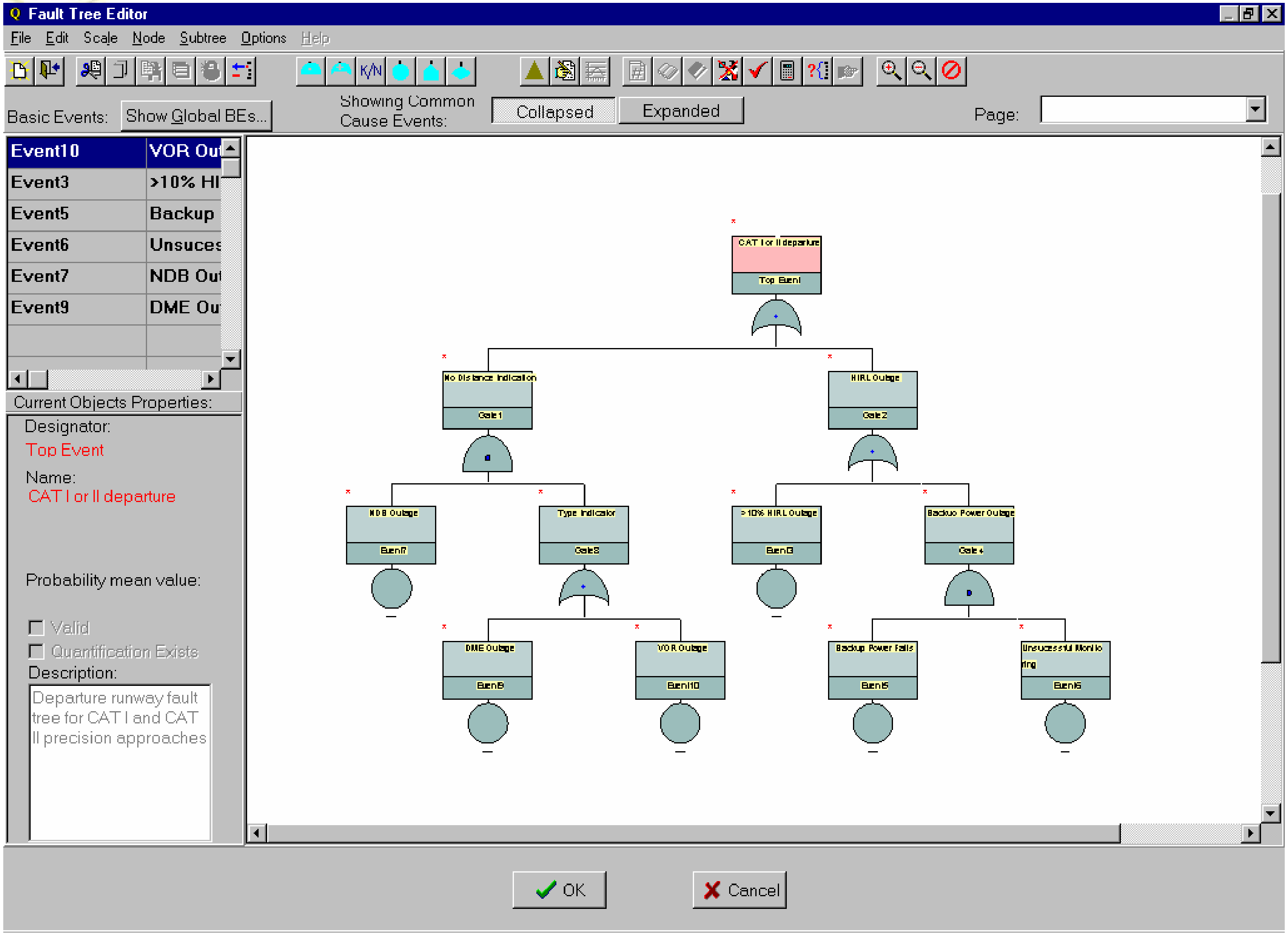
Outages by NAPRS Cause Code

Total Downtime by NAPRS Cause Code

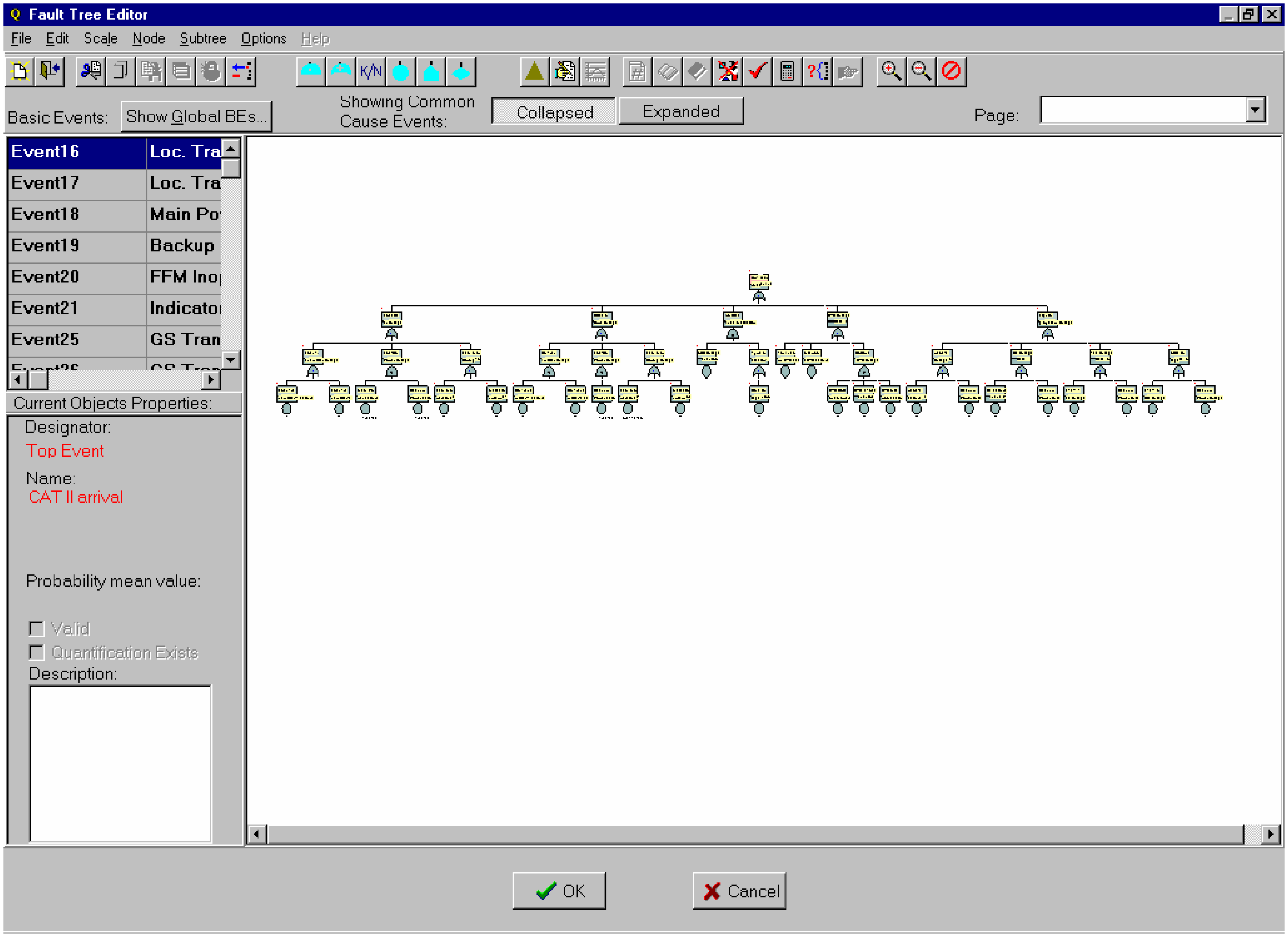
Runway Configuration Information

Percent Occurrence of Weather Categories by Month, Daytime Hours

QRAS Software



QRAS Software

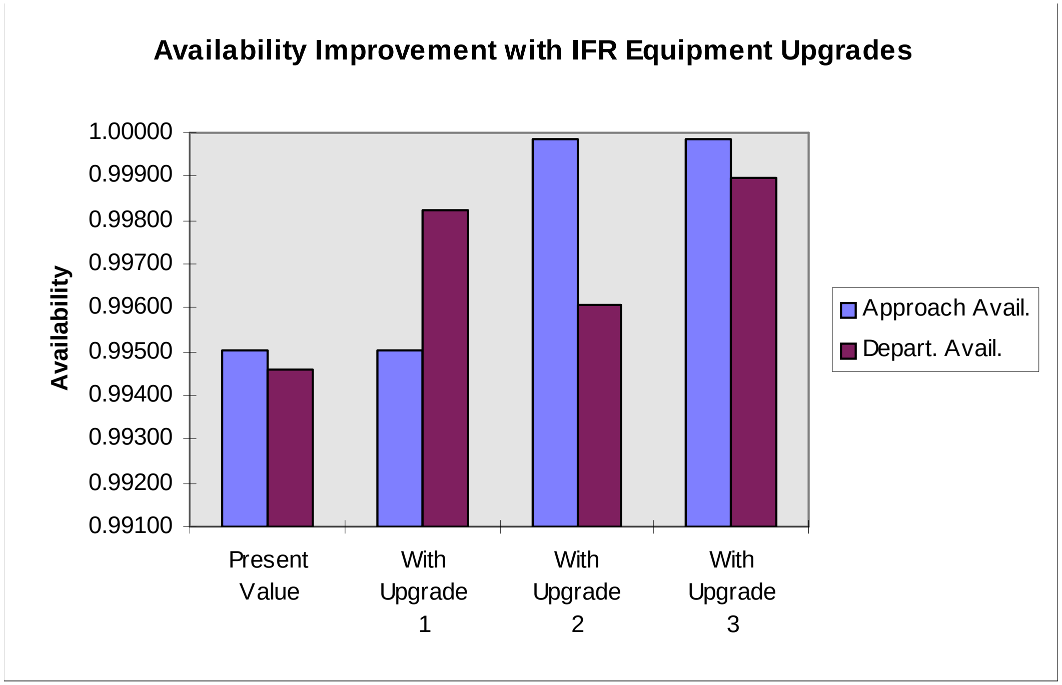


Parameter	Description	Availability
A_A	Airport Arrival Availability	0.9950
A_D	Airport Departure Availability	0.9946
A_{AC1}	Arrival Availability for Configuration 1	0.9982
A_{DC1}	Departure Availability for Configuration 1	0.9931
A_{AC2}	Arrival Availability for Configuration 2	0.9573
A_{DC2}	Departure Availability for Configuration 2	0.9931
A_{AC3}	Arrival Availability for Configuration 3	1.0000
A_{DC3}	Departure Availability for Configuration 3	0.9965
A_{AC4}	Arrival Availability for Configuration 4	0.9989
A_{DC4}	Departure Availability for Configuration 4	0.9965

Arrival and Departure Configuration Availabilities

Parameter	Description	Availability
A_{AR4L}	Arrival Availability, Runway 4L	0.9573
A_{DR4L}	Departure Availability, Runway 4L	0.9580
A_{AR4R}	Arrival Availability, Runway 4R	0.9989
A_{DR4R}	Departure Availability, Runway 4R	1.0000
A_{AR11}	Arrival Availability, Runway 11	0.9573
A_{DR11}	Departure Availability, Runway 11	0.9580
A_{AR22L}	Arrival Availability, Runway 22L	0.9573
A_{DR22L}	Departure Availability, Runway 22L	0.9580
A_{AR22R}	Arrival Availability, Runway 22R	0.9170
A_{DR22R}	Departure Availability, Runway 22R	0.9170
A_{AR29}	Arrival Availability, Runway 29R	0.9170
A_{DR29}	Departure Availability, Runway 29R	0.9170

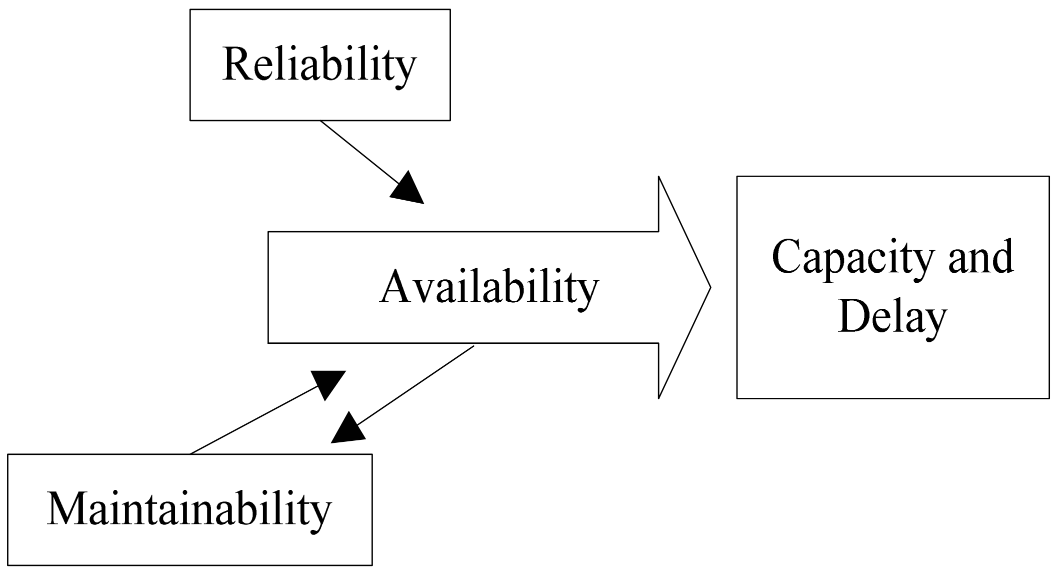
Arrival and Departure Configuration Availabilities



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



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

Decision	Cost State (probability)	Expected cost due to caused traffic delays Cd	Maintenance Cost Cm	Total Cost Ct = Cd + Cm
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	\$ 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

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

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

Markov Decision Process
Linear Programming and Optimal Policies

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 $\boldsymbol{C}_{iaj}$ of equipment j in condition i when action a is employed.

The user cost $\boldsymbol{U}$ is calculated from the overall condition of the airport.

$\boldsymbol{Budget}_j$ 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 $$\sum_i \sum_a \sum_j [C(i,a,j)] \times W_{iaj} + U(f(A, \eta, \text{pax-cost}))$$

Constraint (1): mass conservation constraint

In order to make sure that the mass conservation hold, the sum of all fractions has to be 1.

$$\sum_i \sum_a W_{iaj} = 1 \qquad \forall j$$

Constraint (2): All fractions are greater than 0

$$W_{ia} \geq 0 \qquad \forall a, \forall i$$

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

$$\sum_i \sum_a W_{iaj} * P_j(k \mid i, a) = \sum_a W_{kaj} \qquad \forall j$$

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

$$C(i, a, j) \geq 0 \qquad \forall i, a$$

Constraint (7): Budget constraint

$$\sum_{i}\sum_{a} C(i, a, j) \text{ x } W_{iaj} \leq Budget_{j} \qquad \forall j$$

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, 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

Maintenance cost ($/hr)			
	action 1	action 2	action 3
condition 1	1000	1500	2000
condition 2	800	1200	1500
condition 3	600	900	1000

Numerical Example

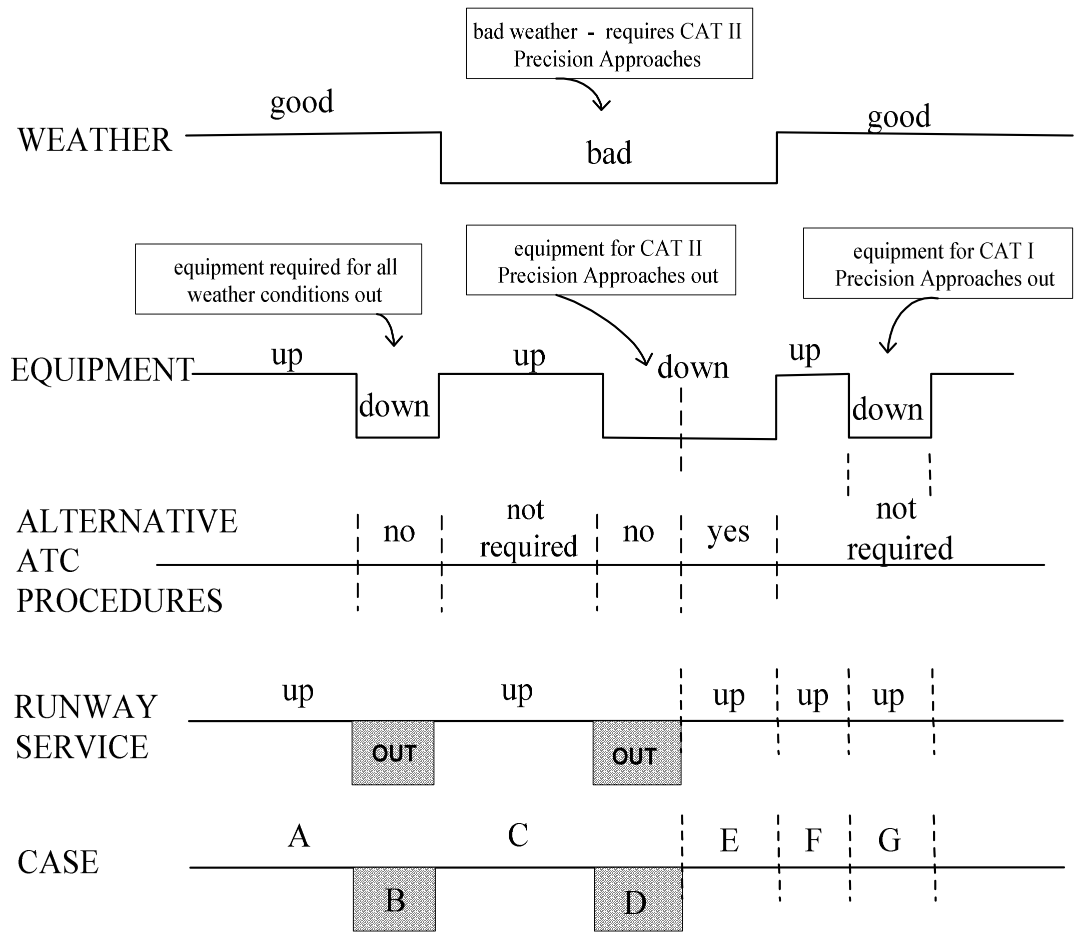
- The availability of the runway is calculated from the fault tree. Fault trees for arrivals and departures are different.
- To calculate the user cost, we use the availability for each condition state to calculate the expected down-time/year (the period that the airport can't operate due to outages). 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 affect airport performance differently, depending on the visibility, wind conditions, noise constrains, primary runway configuration in use and ATC procedures.

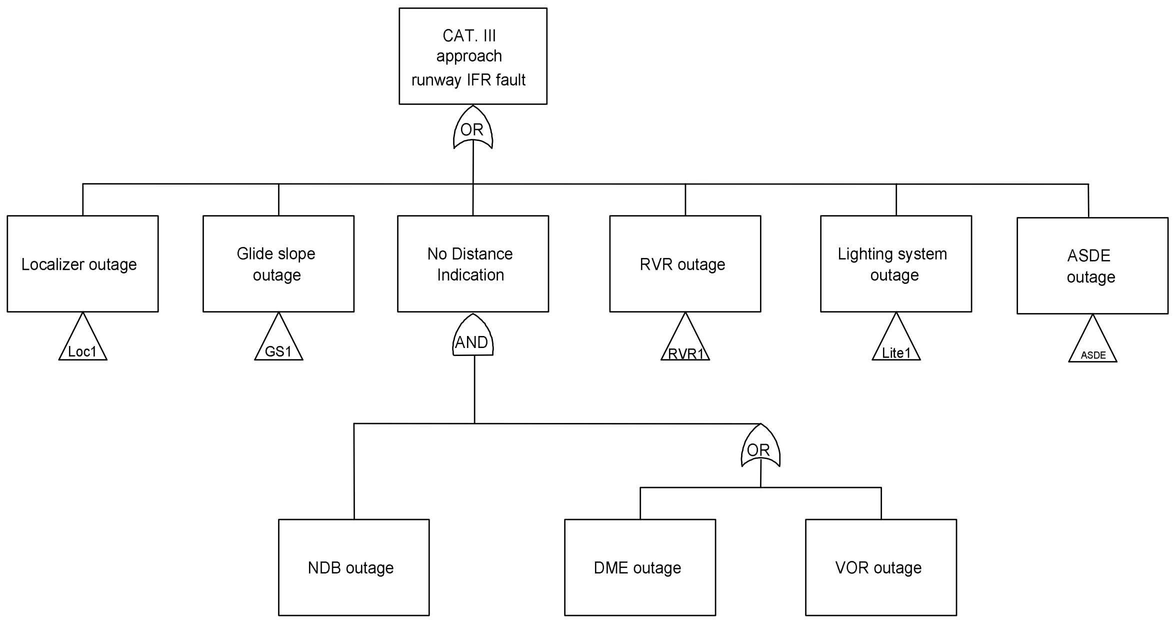
- Consequences of equipment outages are also airport specific.

Numerical Example



Runway Service Alternatives

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

W_{iaj}	action			
condition		1	2	3
	1	0	0	0
	2	0	0	0
	3	0	0	1

Total cost is W_{iaj} x C_{iaj} + U = 210000 + 0 = $210000/year

Assume: budget = \$200000/year

W_{iaj}	Action			
		1	2	3
condition	1	0	0	0.05069
	2	0.101378	0	0
	3	0	0.10138	0.746553

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:

$$Arr_t = \begin{cases} Capacity_t = \beta_{0t} + \sum_{n=1}^{N} \beta_{nt} x_{nt} + \varepsilon_t, & if\ \beta_{0t} + \sum_{n=1}^{N} \beta_{nt} x_{nt} + \varepsilon_t < Demand_t \\ Demand_t, & otherwise \end{cases}$$

$$Dep_t = \begin{cases} Capacity_t = \beta_{0t} + \sum_{n=1}^{N} \beta_{nt} x_{nt} + \varepsilon_t, & if\ \beta_{0t} + \sum_{n=1}^{N} \beta_{nt} x_{nt} + \varepsilon_t < Demand_t \\ Demand_t, & otherwise \end{cases}$$

Numerical Example

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

β_{0t} constant to be estimated in the model in time interval ;

β_{nt} nth coefficients to be estimated in time interval ;

x_{nt} nth independent variable in time interval ;

ε_t error term of the model in time interval ;

$Capacity_t$ capacity in time interval ;

$Demand_t$ demand in time interval.

List of VOR Short Unscheduled Outages at SFO

List of VOR Outages at SFO				
Facility Type	**Code Category**	**Interrupt Condition**	**Outage Local Start Date and Time**	**Outage Local End Date and Time**
VOR	80	FL	5/8/01 16:25	5/8/01 18:50
VOR	80	FL	7/24/01 16:50	7/24/01 19:55
VOR	80	FL	8/23/01 14:25	8/23/01 15:25
VOR	80	FL	9/30/01 18:40	9/30/01 19:25
VOR	80	FL	10/14/01 16:12	10/14/01 17:40
VOR	80	FL	10/14/01 16:30	10/14/01 17:40
VOR	80	FL	4/12/02 16:30	4/12/02 18:50
VOR	80	FL	6/5/02 15:19	6/5/02 20:30
VOR	80	FL	7/9/02 14:55	7/9/02 16:44

Analysis Results for ALSF-2s

Runway Configuration (arrivals | departures)	Weather Condition (IFR of VFR)	Time Interval (local)	Dummy Variable	Estimated Affect on Throughput **	t-value	Significance at 0.05 Level	Number of Observations ***
28L, 28R |	VFR	18:00 pm-22:00 pm	Outage* (occurred)	0.2904	0.30	0.7628 (not significant)	1684
1L, 1R	VFR	18:00 pm-22:00 pm	Outage	1.127	1.16	0.2452 (not significant)	1684
28L, 28R |	IFR	18:00 pm-22:00 pm	Outage	19.4989	0.00	0.9999 (not significant)	5759
1L, 1R	IFR	18:00 pm-22:00 pm	Outage	-3.2371	-0.92	0.3590 (not significant)	5759

* 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.