Analysis of ATM Performance during Equipment Outages

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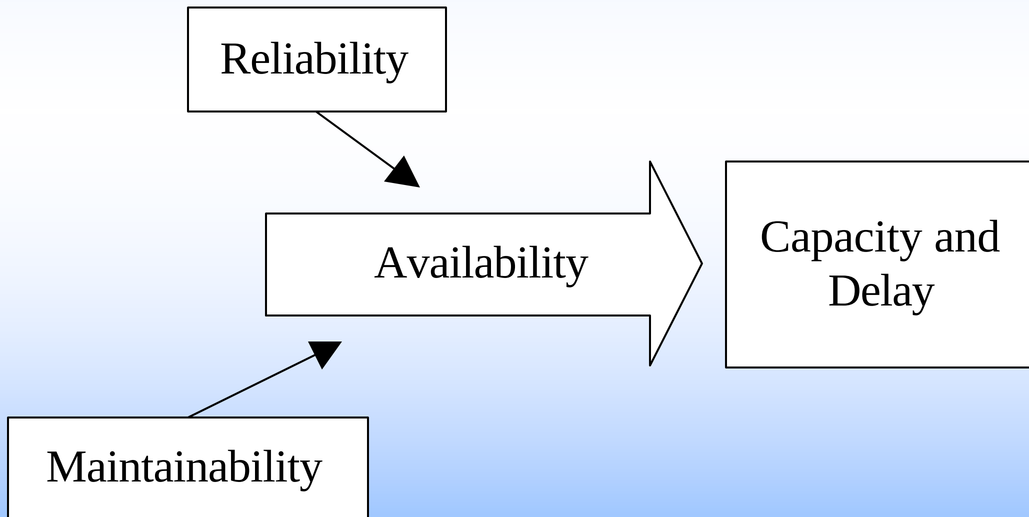
Introduction

The Federal Aviation Administration (FAA) statistics:

- 45,000 total commissioned systems that provide air traffic management (ATM) services
- More than forty percent (48 of 110) of the air route surveillance radars have an average age of 30 years

- The outage of the power supply to the radar displays at the Oakland ARTCC affected Northern California, western Nevada and 18 million square miles of the Pacific Ocean. The controllers' radio and radar systems were down for up to 2 hours (in some areas)
- In Miami, radar's screens were down for 84 minutes (the same month)
- On average, the FAA experiences 12,000 outages a month; 90% is planned and 10% is unplanned"

Relevant Measures of Performance and their Relations



Problem Statement

- Given the NAS architecture, define and determine availability, maintainability, capacity and delay measures of performance while considering equipment outages.

Develop methods to evaluate the effects of system characteristics and policy decisions on system performance

Objectives and Scope

- Identify and define various factors that affect airport and terminal area capacity, delay, availability, maintainability, and reliability
- Develop models for these measures of performance (MOPs)
- Analyze the airport/airspace and cost center performance for the above MOPs.

Literature Review

Capacity Models

- Analytic models
  - Airport, Terminal Airspace and Sector
  - Air Transportation Network
- Commercial Simulation and Analytical Software
  - Capacity and Delay
  - Conflict Detection and Resolution
  - Human/Automation
  - Cost Benefit Analysis
  - Noise Models

Literature Review

Availability Models

- Analytic models
- Simulation models

Models that consider equipment outages are rare.

Models that consider airport/airspace operations jointly with outages and maintenance actions were not found.

Methodology

1) Preliminary qualitative analysis: system definitions and operations, classifications, MOPs and factors

2) Deterministic models:

(a) A deterministic aircraft separation model is used to estimate capacity. This method is useful for quick estimates of the number of aircraft operations per facility under some predefined conditions (i.e., mile-in-trail separation and aircraft mix).

However, these methods do not provide delay estimates.

Methodology

(b) A deterministic queuing approach is then used to estimate capacity and delays due to single outages for a hypothetical airport (i.e., to estimate the impact of outages on runway throughput) and terminal airspace area.

Deterministic queuing analysis is used for calculating aircraft delays, numbers of aircraft experiencing queuing, and queue duration. This method can handle traffic conditions where both the arrival and service rates vary over time.

Methodology

3) Stochastic queuing model:

nested queuing model

4) Analytic model for airport availability using Fault Tree Analysis (FTA)

5) Simulation models for Maintenance Cost Center and Airport Operations

Deterministic Aircraft Separation Method

- we consider arrivals only, and assume that the runway occupancy time is not the bottleneck in the system

- if C_r: runway capacity (flights/hour)
  - T_i : time when lead aircraft *i* passes over runway threshold
  - T_j : time when following aircraft *j* passes over runway threshold
  - $[T_{ij}] = T_j - T_i$: matrix of actual time separations at runway threshold for two successive arrivals, an aircraft of speed class *i* followed by an aircraft of speed class *j*
  - p_{ij} : probability that a lead aircraft of class *i* will be followed by a trail aircraft of class j
  - $E[T_{ij}] =$: expected value of T_{ij}, i.e., mean service time

Capacity is $$C_r = \frac{1}{E[T_{ij}]}$$

Degraded Capacity

$$c_r^d = \begin{cases} 0 & \text{, if ILS fails} \\ \dfrac{1}{E[affected\, matrix T_{ij}]} & \text{, if other equipment fails} \end{cases}$$

Capacity Loss $$c_r^l = \begin{cases} all\ (C_r) & \text{, if ILS fails} \\ C_r - \dfrac{1}{E[affected\ matrix\ T_{ij}]} & \text{, if other equipment fails} \end{cases}$$

Deterministic Queuing Analysis

Varying Service Rate Case

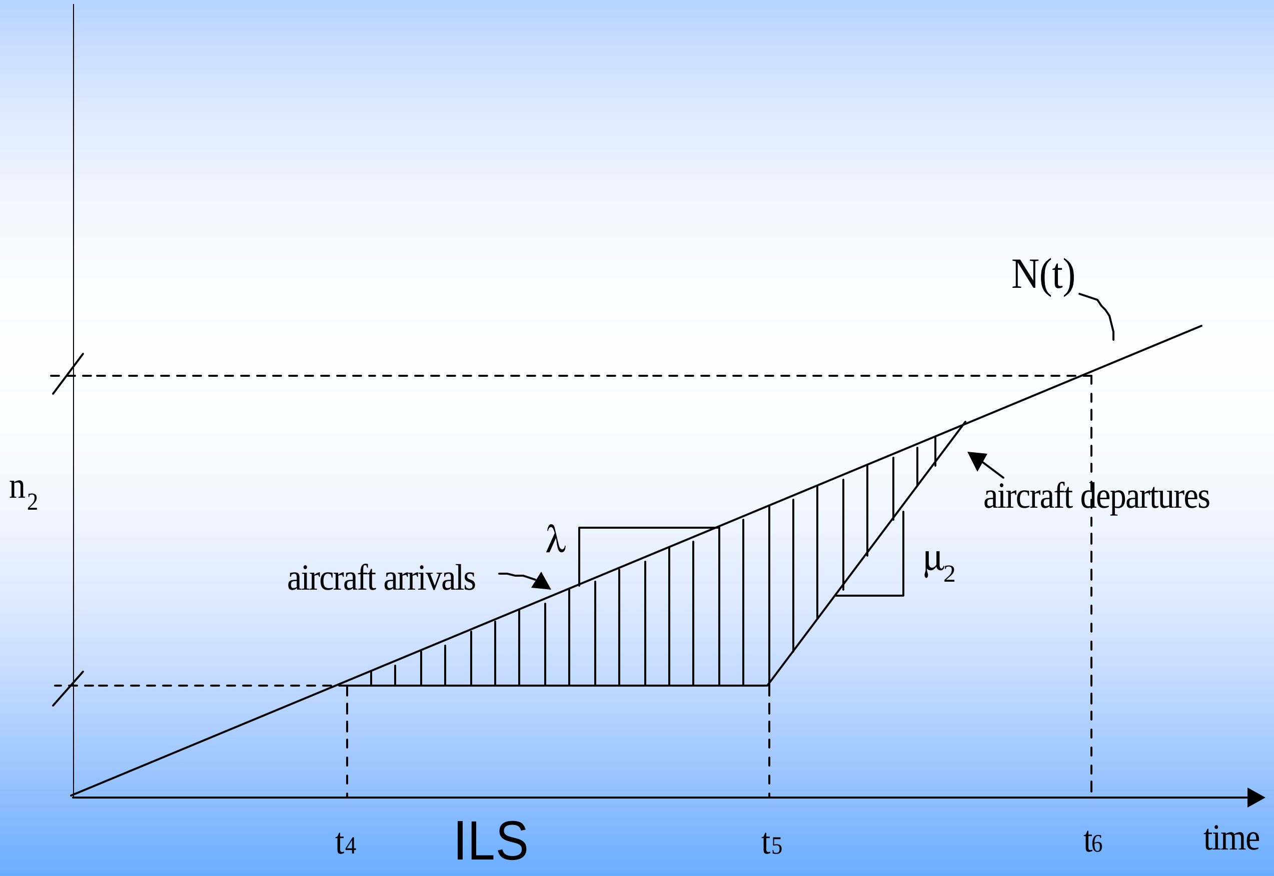
- Deterministic queuing analysis is applied at a macroscopic level, i.e. by modeling continuous aircraft flows rather than individual aircraft.

Pulsed Service Problem

- the arrivals to the terminal area or an airport (i.e., runway) have a constant arrival rate (*l* = aircraft/hour) but the service rate (*m* = aircraft per hour) is "pulsed" (time-dependent) and may be defined as follows:

$$m = \begin{cases} 0 & \text{, if the ILS or any equipment that closes the server is out} \\ m_2 & \text{, if the equipment functions} \end{cases}$$

Deterministic Queuing Diagram for ILS Outages



The following measures can be calculated for given

e: time equipment is functioning
r: outage time and
L: time length ($L=e+r$):

1) Queue duration: $$t_Q = \frac{m_2 \times r}{m_2 - l}$$

2) Number of aircraft experiencing queue: $N_Q = (l \times t_Q)/3600$

3) Average aircraft delay: $$d = \frac{r \times t_Q}{2L}$$

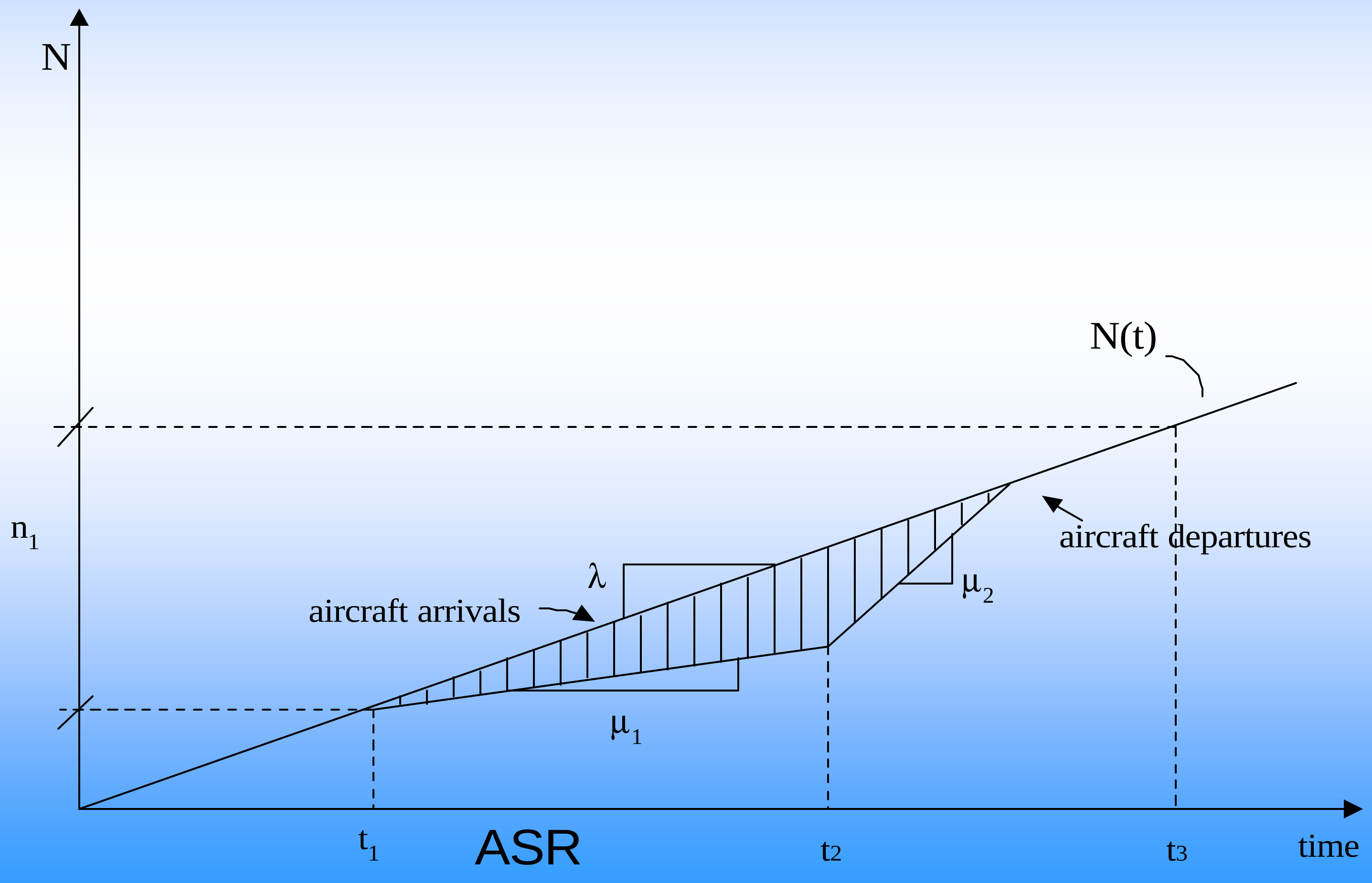
4) Total delay : $$T_d = \frac{r \times t_Q \times l}{2}$$

- This model is applicable to the precision approaches for CAT I, II and III.

Varying Service Rate

- the arrival rate is constant
- the service rate is varied (i.e., degraded) due to the equipment failures but the server (i.e., runway) is not completely closed

Deterministic Queuing Diagram for ASR Outages



The service rate is defined as:

$$m = \begin{cases} m_1 & \text{, if ASR or any other equipment that degrades server fails} \\ m_2 & \text{, if equipment functions properly} \end{cases}$$

The same measures could be calculated:

1) Queue duration

2) Number of aircraft experiencing queue

3) Average aircraft delay

4) Total delay

Nested Queuing Model

- This model jointly considers two different systems

First System: terminal airspace

aircraft = customers

navigational fixes = servers

Second System: maintenance cost center

repairs = customers

technicians = servers

Nested Queuing Model

- Basic assumptions:

First System: M/M/k “classical” queuing system

Second System: M/M/1 machine repair system

Model is useful for interrelated activities
(such as a relation between the aircraft operations and technician activities)

Availability Modeling for Airports

- Traditional availability estimates consider weather and equipment availability separately.

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

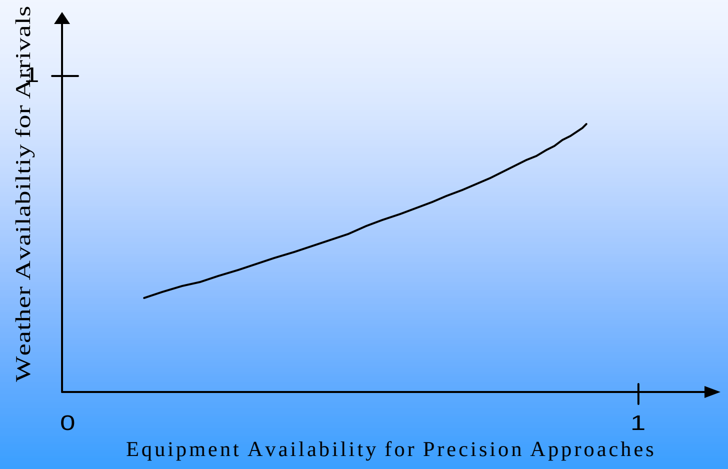
$$A_{op} = (t_s - t_{down}) / t_s$$

Weather Availability: $A_w = \dfrac{MTBC}{MTBC + MTTC_w}$

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.

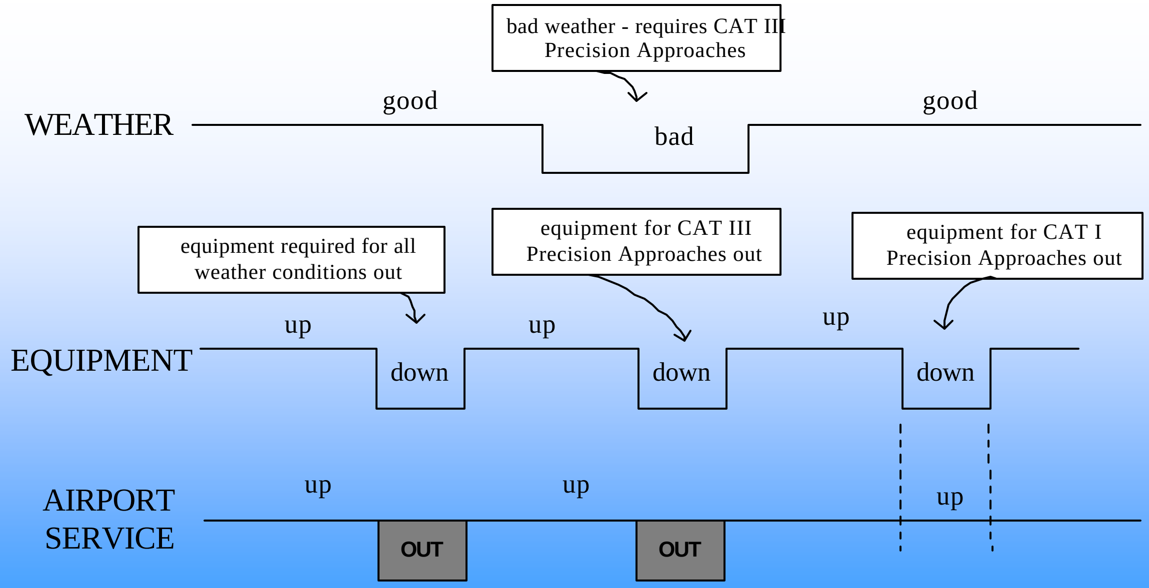


Relation between
Weather Availability for Arrivals
and Equipment Availability
for CAT III Approaches

Availability Modeling for Airports

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

Availability Modeling for Airports

Conceptual approach for availability estimation:

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

Availability Modeling for Airports

Conceptual approach for availability estimation:

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

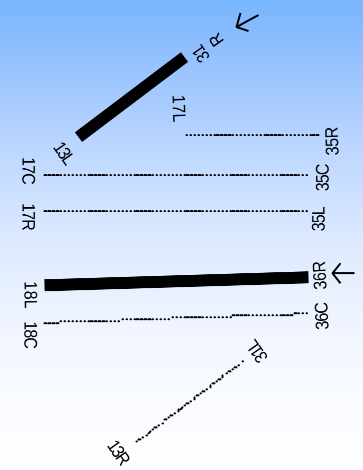
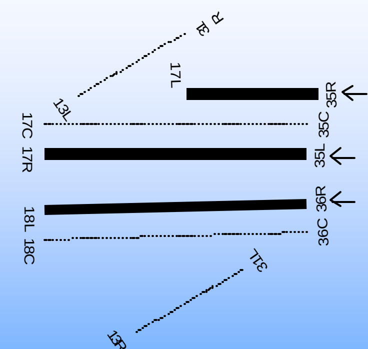
C : weather category

Availability Modeling for Airports

Conceptual approach for availability estimation:

2) single runway availability is combined with the availability of other runways, which are used within a particular runway configuration.

(If an airport has several runways, the number of runway configurations is more than one.)

Primary wind direction w	Noise Constraint N	Runway configuration f	Primary Runways in Use R
w_1 = North	None	f_1	 runways: 31R and 36R
w_1 = North	None	f_2	 runways: 35R, 35L, and 36R
w_1 = North	None	f_3	Runways: 35C and 36C
w_2 = South	None	f_1	Runways: 13R, 17L
w_2 = South	None	f_2	Runways: 13R, 17C and 18R

Availability Modeling for Airports

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

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

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

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*

Simulation Methodology for the Maintenance Cost Center and Airport Operations

- Two different systems are modeled:

  Maintenance Cost Center and Airport Operations

- Maintenance Cost Center estimates the impact of

(a) actual repair rates

(b) number of available technicians

(c) average maintenance rate per facility

(d) failure rate per facility

(e) distribution of technicians by shifts and training, and

(f) travel time

on

(1) equipment outage time, (2) equipment availability and

(3) technician utilization

Simulation Methodology for the Maintenance Cost Center and Airport Operations

The Airport Model deals with:

(a) transient demand conditions

(b) dissimilar aircraft types

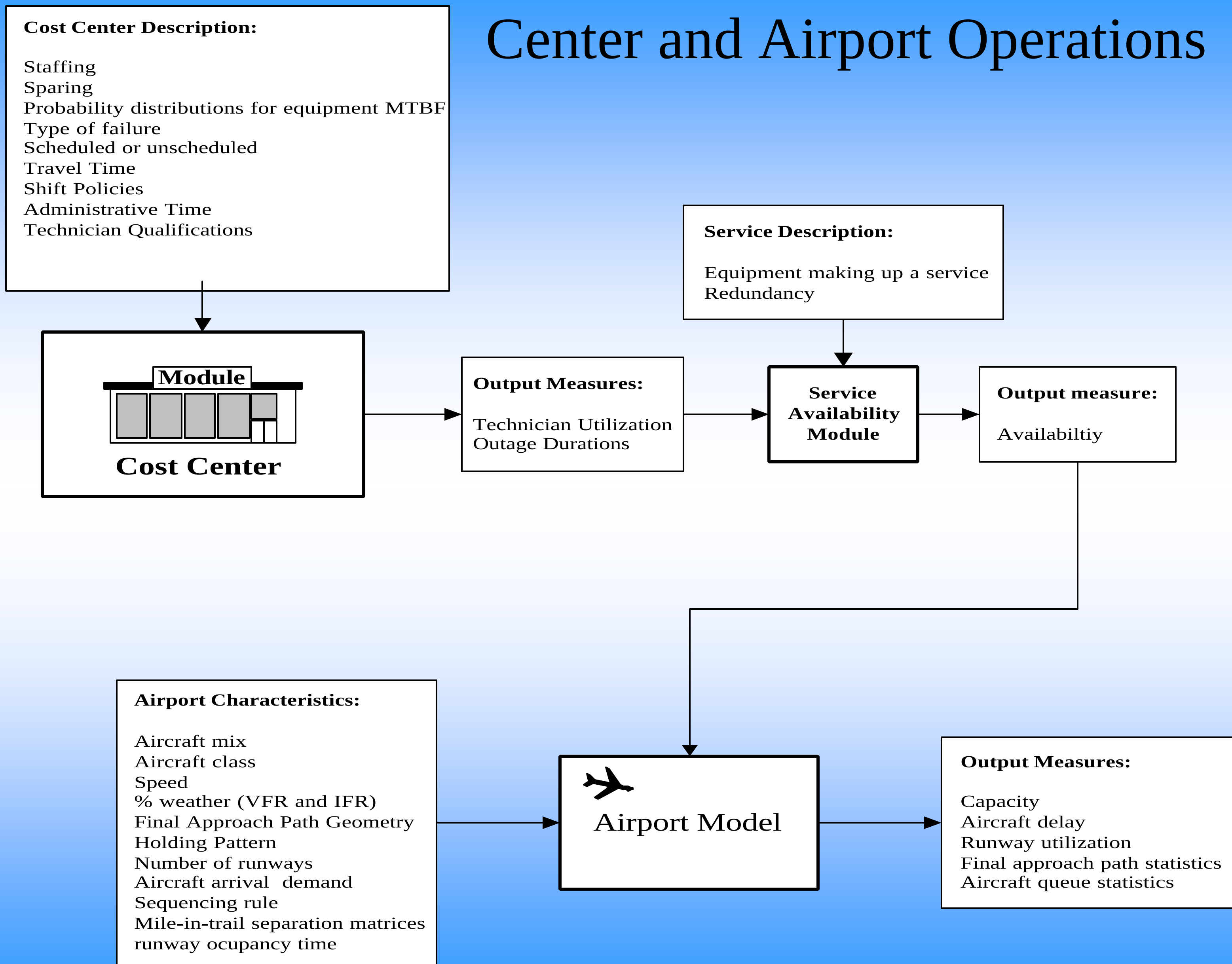
(c) different flight rules

(d) dissimilar runways, etc...

and estimates

(1) airport delays - total aircraft delay in the system, airspace aircraft delay, runway delay, (2) utilization - for holdings (over a navigational air), final approach path and runways, (3) aircraft queue statistics, (4) total aircraft time spent in the system.

Simulation Methodology for the Maintenance Cost Center and Airport Operations



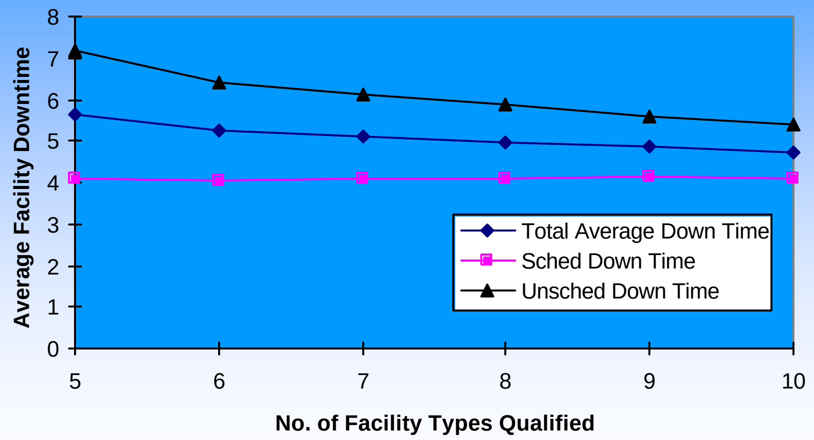
Conceptual Framework for Preliminary Simulation Models

Selected Results

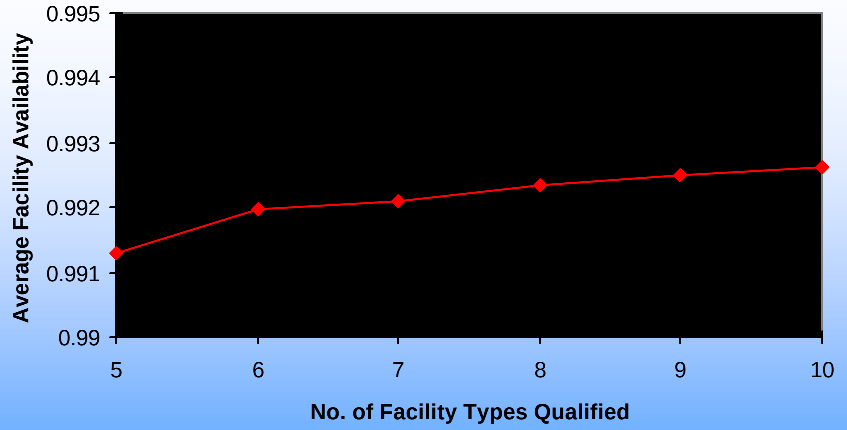
Effects of Aircraft Arrival Rate and Technician Service Rate on Repairs Backlog

	β (mean service rate in System II = jobs/hour)			
λ (aircraft arrival/hour)	2.9	3.1	3.3	3.5
14	0.22083	0.15416	0.0875	0.020834
19	1.0028	0.935417	0.86875	0.802084
24	1.7833	1.71667	1.65	1.58334
29	2.56458	2.497917	2.43124	2.36458
34	3.3458	3.279167	3.2125	3.14583
39	4.127083	4.060417	3.99375	3.92708
44	4.9083	4.84166	4.775	4.7083
49	5.689	5.62291	5.55625	5.4896
54	6.47083	6.404167	6.3375	6.27083
59	7.25	7.185417	7.11	7.05208
64	8.03	7.966665	7.9999	7.83333

Selected Results: Cost Center



Average Facility Downtime vs. Technician Training



Availability vs. Technician Training

Recommendations

- Explore further optimization techniques for technician assignments
- Consider new technology (such as GPS) in availability and capacity modeling
- Conduct Cost/Benefit analysis considering passenger costs