Airfield Capacity

Amedeo R. Odoni

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- **Objective**
  - To summarize fundamental concepts re. airfield capacity
- **Topics**
  - Definitions of capacity
  - Factors affecting capacity
  - Separation requirements
  - A simple model for a single runway
  - Capacity envelopes and capacity coverage chart

Capacity Measures

- **Maximum-Throughput Rate**
  - **Average number of demands a server can process per unit of time when always busy**
    - m = maximum throughput rate
    - E(t) = expected service time

$$m = \frac{1}{E(t)}$$

- **Level of Service (LOS) related capacity**
  - **Number of demands processed per unit of time while meeting some pre-specified LOS standards (must know m to compute)**

Capacity Definitions

- **Maximum Throughput (or Saturation) Capacity**

  The expected ("average") number of operations (takeoffs and landings) that can be performed in one hour on a runway without violating ATC rules, assuming continuous aircraft demand.

- **Practical Hourly Capacity**

  The average number of operations that can be performed in one hour on a runway with an average delay per operation of 4 minutes.

Note: Definitions can also be extended to entire runway system.

Capacity Definitions (2)

- **Sustained Capacity**

  The average number of operations per hour that can be "sustained" for periods of several hours; vaguely-defined, workload-related, limited use; in US typically set to about 90% of saturation capacity in VMC, near 100% in IMC

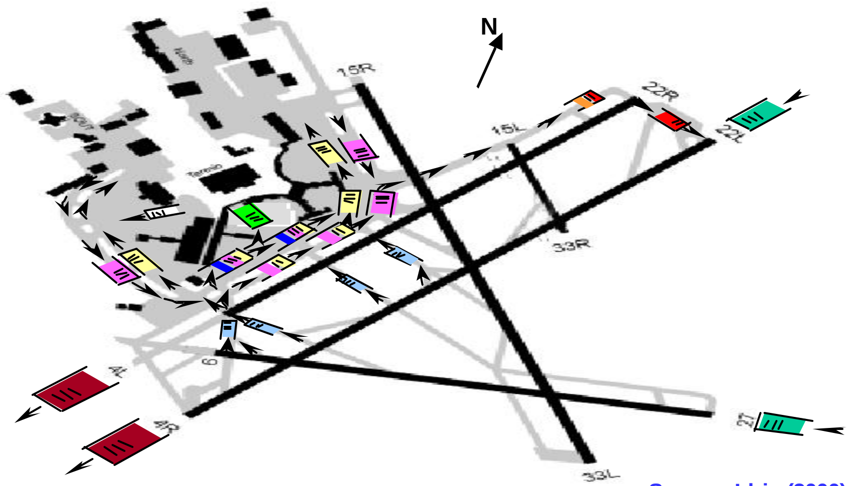
- **Declared Capacity**

  The capacity per hour used in specifying the number of slots available for schedule coordination purposes; used extensively outside US; no standard method for its determination; generally set to about 85-90% of saturation capacity; may be affected by apron capacity and terminal capacity

Factors Affecting Capacity

- Number and layout of active runways
- Separation requirements (longitudinal, lateral)
- Weather (ceiling, visibility)
- Wind (direction, strength)
- Mix of aircraft
- Mix and sequencing of operations (landings, takeoffs, mixed)
- Quality and performance of ATM system (including human factor -- pilots and controllers)
- Runway exit locations
- Noise considerations

Configuration 22L/27 - 22R/22L



Source: Idris (2000)

Role of ATC Separation Requirements

- Runway (and airfield) capacities are constrained by ATC separation requirements
- Typically aircraft are separated into a small number (3 or 4) of classes
- Example: FAA classification
  - Heavy (H): 255000 lbs < MTOW
  - Large (L): 41000 lbs < MTOW < 255000 lbs
  - Small (S): MTOW < 41000 lbs
- Required separations (in time or in distance) are then specified for every possible pair of aircraft classes and operation types (landing or takeoff)
- Example: "arrival of H followed by arrival of S"

IFR Separation Requirements: Single Runway (USA)

Arrival-Arrival:

(1) Airborne separations on final approach (nmi):

Leading aircraft	Trailing aircraft: H	L or B757	S
H	4	5	5/6*
B757	4	4	5
L	2.5 (or 3)	2.5 (or 3)	3/4*
S	2.5 (or 3)	2.5 (or 3)	2.5 (or 3)

** Applies when leading aircraft is at threshold of runway*

(2) Leading aircraft must be clear of the runway before trailing aircraft touches down

IFR Separation Requirements: Single Runway (USA) [2]

Departure-Departure (approximate, in seconds)

Leading aircraft	Trailing aircraft: H	L + B757	S
H	90	120	120
B757	90	90	120
L	60	60	60
S	45	45	45

Arrival-Departure and Departure-Arrival

- **Leading aircraft must be clear of runway at the instant when trailing aircraft starts takeoff roll or touches down on the runway, respectively. In D-A case, trailing arrival must also be at least 2 nmi from runway when takeoff run begins**

Separation Requirements (Italy; until recently)

Arrival/Arrival (in nautical miles)

$$\begin{array}{c} \\ H \\ M/L \\ S \end{array} \begin{array}{c} \begin{array}{ccc} H & M/L & S \end{array} \\ \begin{bmatrix} 5 & 5 & 7 \\ 5 & 5 & 5 \\ 5 & 5 & 5 \end{bmatrix} \end{array}$$

Departure/Departure

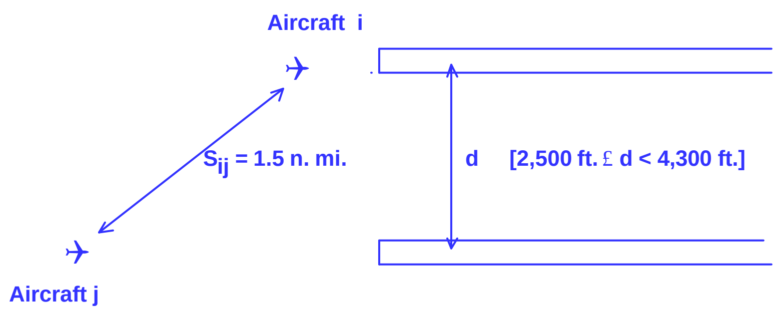
120 seconds between successive departures

- **Departure/Arrival**
  - Arrival must be at least 5 n.mi. away from runway threshold

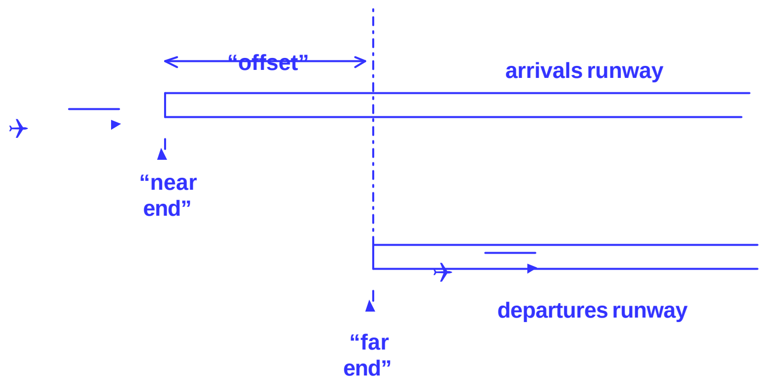
Parallel Runways (IFR): USA

Separation between runway centerlines	Arrival/ arrival	Departure/ departure	Arrival/ departure	Departure/ arrival
700-2499 ft	As in single runway	As in single runway	Arrival touches down	Departure is clear of runway
2500- 4300 ft	1.5 nmi (diagonal)	Indep'nt	Indep'nt	Indep'nt
4,300 ft or more	Indep'nt	Indep'nt	Indep'nt	Indep'nt

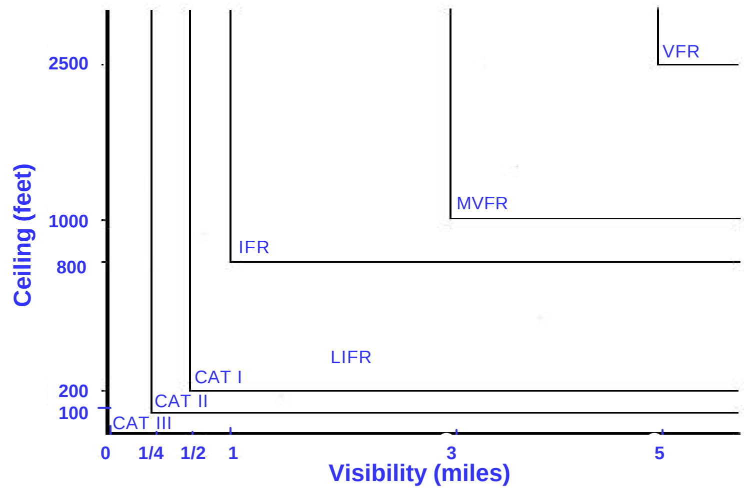
The diagonal separation between two aircraft approaching medium-spaced parallel runways



Staggered parallel runways; the "near" runway is used for arrivals and the other for departures



Typical classification of weather conditions (ceiling and visibility) at an airport in the United States

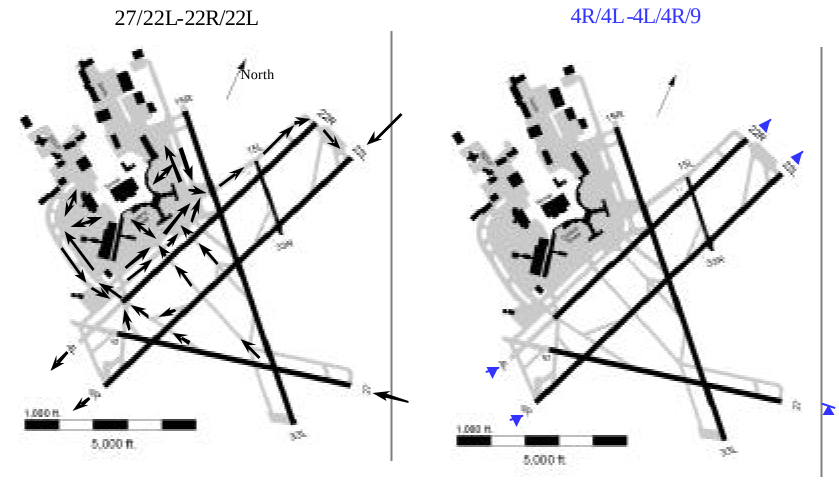


Weather Category (%) By Season -- *Boston Logan Airport*

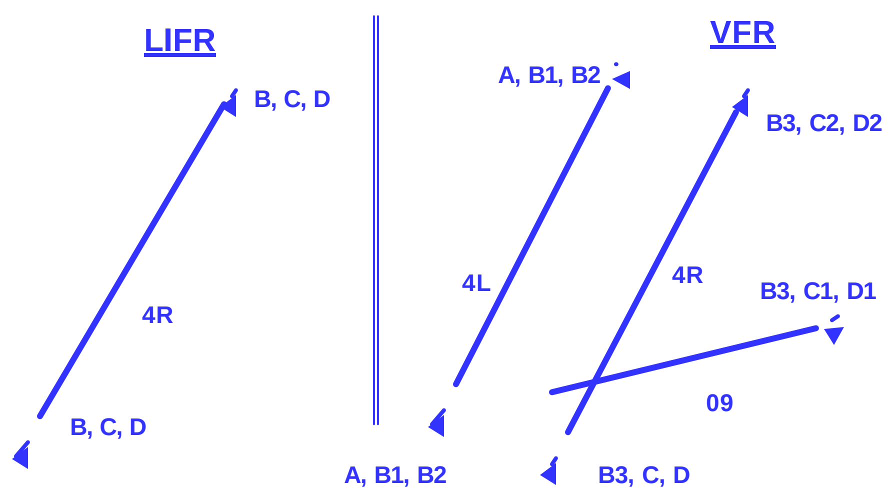
Season

Weather Category	Spring	Summer	Fall	Winter	Annual
VFR1	79.19	78.78	80.03	77.94	78.99
VFR2 / IFR1	10.26	13.86	11.73	12.42	12.07
IFR2	7.95	5.83	6.43	6.89	6.78
IFR3	.08	.08	.19	.02	.09
IFR4	2.50	1.45	1.63	2.80	2.07

Two high-capacity configurations with opposite orientations at Boston/Logan



Configurations: Same Direction, Different Weather Conditions



Typical Approach for Estimating Airside Capacity

1. Compute average time interval for all possible aircraft class pairs i, j

   t_{ij} = average time interval between successive movements of a pair of aircraft of types i and j (i followed by j) such that no ATC separation requirements are violated

2. Compute probability for all i, j

   p_{ij} = probability of occurrence of the pair of aircraft types i and j (i followed by j)

3. Compute overall average service time

$$E(t) = \sum_i \sum_j p_{ij} \cdot t_{ij} \qquad m = \frac{1}{E(t)}$$

Numerical Example

Given: Single Runway (Arrivals Only: IFR)

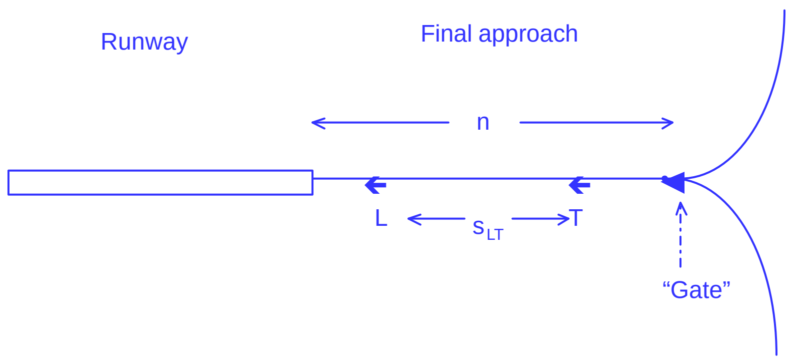
n = 5 N. Miles

Aircraft Types			
Type	Mix (%)	Approach Speed (kts)	Runway Occupancy Time (secs)
Heavy (1)	20	140	60
Large (2)	50	120	55
Small (3)	30	100	50

$$[s_{ij}] = \begin{array}{c} \\ 1 \\ 2 \\ 3 \end{array} \begin{array}{c} \begin{array}{ccc} 1 & 2 & 3 \end{array} \\ \begin{bmatrix} 4 & 5 & 6^* \\ 3 & 3 & 4^* \\ 3 & 3 & 3 \end{bmatrix} \end{array}$$

* Applies only with lead aircraft at threshold (all other separations apply throughout final approach).

A simple representation of a runway used for arrivals only under IFR



Single Runway Model

- *(Arrivals Only: IFR)*

- **Separation Requirements**
  - Airborne longitudinal separation
    - **3 - 6 n. miles, depending on aircraft pair, as shown in matrix of example**
  - Runway occupancy separation
    - **no two aircraft simultaneously occupy the runway**

Effect of Airborne Separation Requirement

✈ Closing Case

- Second aircraft is faster, and must have required separation distance from first aircraft at runway threshold; separation at merge is greater than minimum.

✈ Opening Case

- Second aircraft is slower, and must meet separation requirement from first aircraft in merge area when approach is initiated; separation at runway threshold is greater than minimum.

Appendix: Single Runway Model

Consider two aircraft, i and j

Let n = length of final approach (typically 5-8 n.mi.)
s_{ij} = separation in air between i and j
v_i, v_j = approach speed of i, j
O_i, O_j = runway occupancy time of i, j
$T_{i,j}$ = min. time separation between i and j at runway

Assume $v_i > v_j$

- Opening Case: Aircraft i precedes j

$$T_{ij} = \max\left(\frac{n + s_{ij}}{v_j} - \frac{n}{v_i}, o_i\right)$$

- Closing Case: Aircraft j precedes i

$$T_{ji} = \max\left(\frac{s_{ji}}{v_i}, o_j\right)$$

Matrix of Minimum Separations

✈ The number T_{ij} in row i and column j is the minimum separation(sec) for the case of aircraft type i followed by type j

$$T_{ij} = \begin{bmatrix} 103 & 171 & 216 \\ 77 & 90 & 144 \\ 77 & 90 & 108 \end{bmatrix}$$

- **Opening Case**

$$T_{12} = \max\left(\frac{10\,\text{n.mi.}}{120\,\text{knots}} - \frac{5\,\text{n.mi.}}{140\,\text{knots}},\ 60\,\text{sec}\right)$$

$$= \max(171\,\text{sec},\ 60\,\text{sec}) = 171\,\text{sec}$$

Matrix of Minimum Separations [2]

- **Closing Case**

$$T_{31} = \max\left(\frac{3\,\text{n.mi.}}{140\,\text{knots}},\ 50\,\text{sec}\right)$$

$$= \max(77\,\text{sec},\ 50\,\text{sec}) = 77\,\text{sec}$$

- **Stable Case**

$$T_{22} = \max\left(\frac{3\,\text{n.mi.}}{120\,\text{knots}},\ 55\,\text{sec}\right)$$

$$= \max(80\,\text{sec},\ 55\,\text{sec}) = 80\,\text{sec}$$

- **"Special" Case (also T_{23})**

$$T_{13} = \max\left(\frac{6\,\text{n.mi.}}{100\,\text{knots}},\ 60\,\text{sec}\right)$$

$$= \max(216\,\text{sec},\ 60\,\text{sec}) = 216\,\text{sec}$$

Safety Buffer

- **In practice, a safety buffer is added to the minimum separations between aircraft, to make up for imperfections in the ATC system**
- **Allow a buffer of an additional B = 10 seconds between each aircraft for safety (10 seconds implies about 1/3 n. mi. longitudinal separation)**

Matrix of Average Time Separations

- The number t_{ij} is the average separation (sec) between an aircraft of type i and a following aircraft of type j.

$$t_{ij} = T_{ij} + b$$

$$t_{ij} = \begin{bmatrix} 113 & 181 & 226 \\ 87 & 100 & 154 \\ 87 & 100 & 118 \end{bmatrix}$$

Matrix of Pair Probabilities

- Let p_{ij} = probability that an aircraft of type i will be followed by one of type j
- Assume first-come, first-served (FCFS) runway service

$$p_{ij} = \begin{bmatrix} 0.04 & 0.1 & 0.06 \\ 0.1 & 0.25 & 0.15 \\ 0.06 & 0.15 & 0.09 \end{bmatrix}$$

Example

- **20% of aircraft are Type 1, 50% are Type 2**
- **Therefore, the probability of a Type 1 followed by a Type 2 is: $p_{12} = (0.2)*(0.5) = 0.1$**

***Note*: This is only valid for an FCFS system; no sequencing.**

Numerical Example [2]

Matrix of average time intervals, t_{ij} (in seconds), for all possible pairs of aircraft types:

$$[t_{ij}] = \begin{array}{c} \\ 1 \\ 2 \\ 3 \end{array} \begin{array}{c} \begin{matrix} 1 & 2 & 3 \end{matrix} \\ \begin{bmatrix} 113 & 181 & 226 \\ 87 & 100 & 154 \\ 87 & 100 & 118 \end{bmatrix} \end{array}$$

Matrix of probabilities, p_{ij}, that a particular aircraft pair will occur:

$$[p_{ij}] = \begin{array}{c} \\ 1 \\ 2 \\ 3 \end{array} \begin{array}{c} \begin{matrix} 1 & 2 & 3 \end{matrix} \\ \begin{bmatrix} 0.04 & 0.1 & 0.06 \\ 0.1 & 0.25 & 0.15 \\ 0.06 & 0.15 & 0.09 \end{bmatrix} \end{array}$$

Numerical Example [3]

- By multiplying the corresponding elements of the matrices [p_{ij}] and [t_{ij}] we can compute the average separation (in seconds) between a pair of aircraft on the runway in question.

That is:

$$E(t) = \sum_i \sum_j p_{ij} \cdot t_{ij}$$

★ **E(t) = 124 seconds**

Numerically:

$$E(t) = (0.04)(113) + (0.1)(181) + (0.06)(226) + (0.1)(87) + (0.25)(100) + (0.15)(154) + (0.06)(87) + (0.15)(100) + (0.09)(118)$$

Saturation Capacity $= \dfrac{3600 \text{ seconds}}{124 \text{ seconds}} =$ **29 aircraft**

Numerical Example [4]

- The variance (a measure of variability) of the service times (intervals between successive landings in this case) can also be computed from:

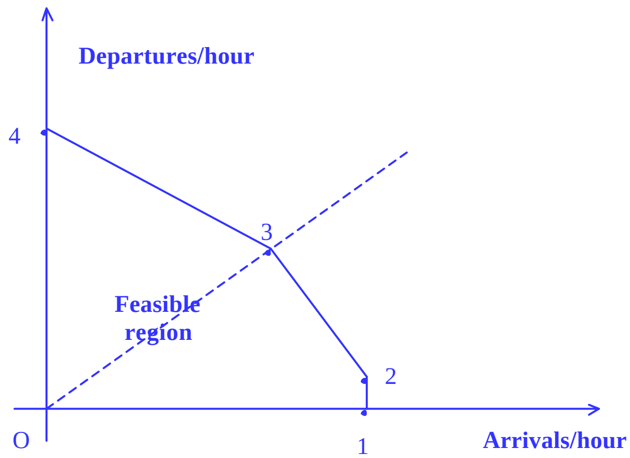
$$\sigma_t^2 = \sum_i \sum_j p_{ij} \cdot [t_{ij} - E(t)]^2$$

- Or,

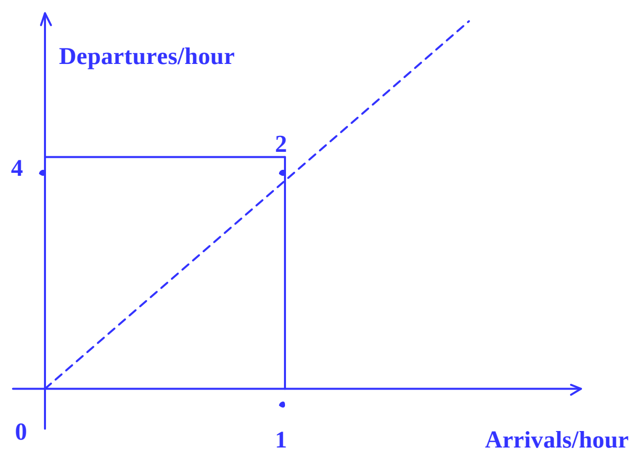
$(0.04)(113-124)^2 + (0.1)(181-124)^2 + \ldots + (0.09)((118-124)^2$
$= 1542 \text{ sec}^2$

- The standard deviation, $\sigma_t = \sqrt{1542} = 39$ seconds

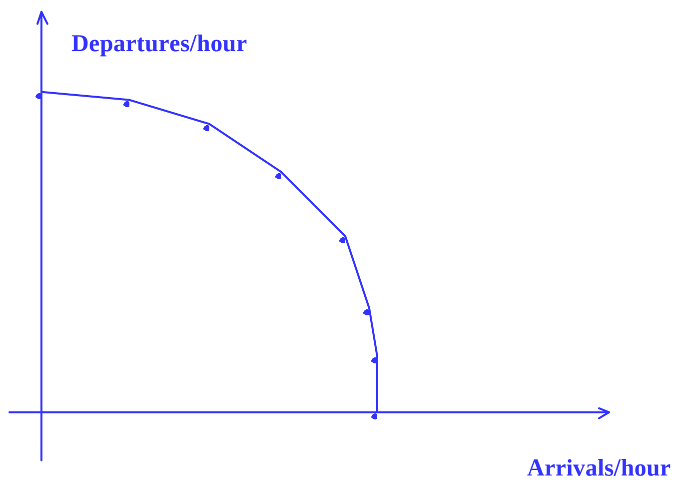
A typical capacity envelope for a single runway



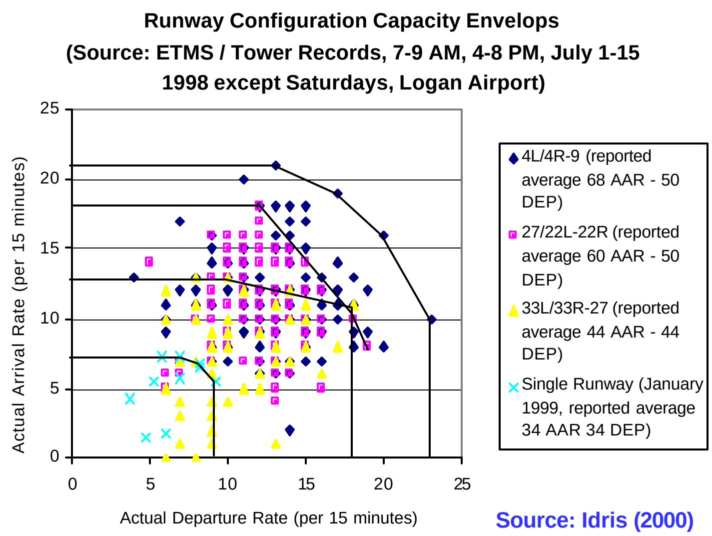
Capacity envelope for two parallel runways, one used for arrivals and the other for departures



A hypothetical capacity envelope for a multi-runway airport with mixed use of the runways



Runway Configuration Capacity Envelopes



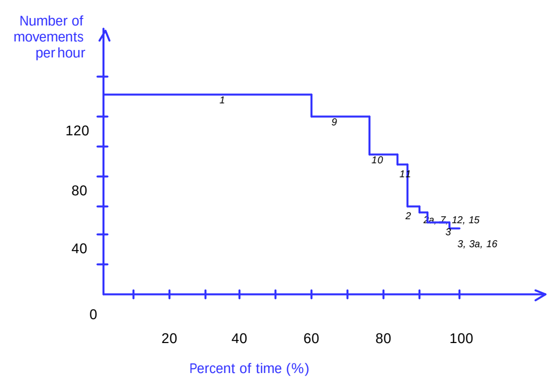
Source: Idris (2000)

Capacity Coverage Chart

- CCC shows how much capacity is available for what percentage of time
- Assumptions:
  - airport will operate at all times with the highest capacity configuration available for prevailing weather/wind conditions
  - the capacity shown is for a 50%-50% mix of arrivals and departures

  Note: Neither of these assumptions is necessarily true in practice (e.g., noise may be principal consideration in selecting configuration during periods of low demand)

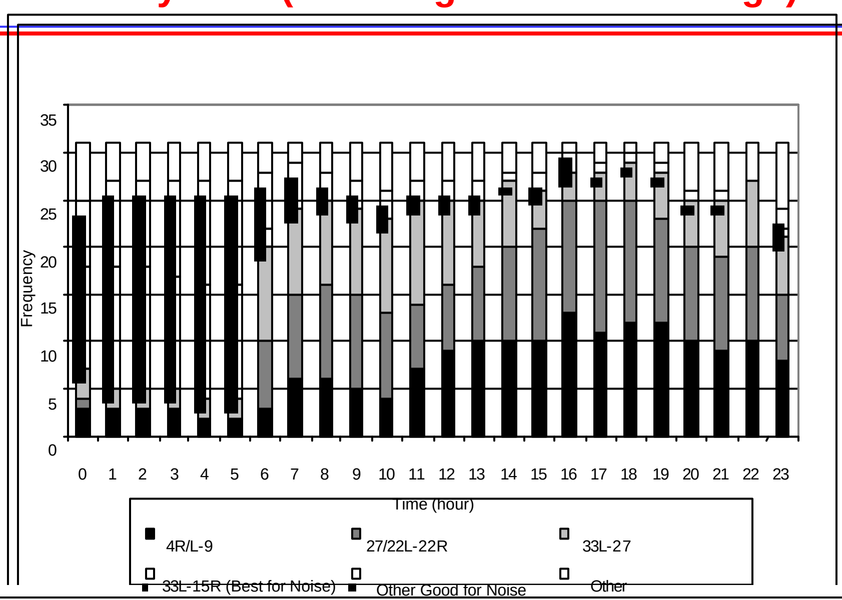
The capacity coverage chart for Boston/Logan



Capacity Coverage Chart [2]

- **The CCC summarizes statistically the supply of airside capacity**
- **CCC requires a capacity analysis for all weather/wind conditions and runway configurations**
- **“Flat” CCC implies predictability and more effective utilization of airside facilities**
  - Operations (takeoffs and landings) can be scheduled with reference to a stable capacity level
  - Fewer instances of under-utilization and over-utilization of facilities

Runway configuration usage at Boston/Logan, January 1999 (from Logan FAA tower logs)



Range of Airfield Capacities

- The capacity of a single runway varies greatly among airports, depending on local ATC rules, traffic mix, operations mix, local conditions and the other factors identified earlier (12- 60+ movements per hour is possible)
- At major commercial airports in developed countries the range is 25-60 movements per hour for each runway
- Depending on the number of runways and the airport's geometric configuration, total airfield capacity of major commercial airports ranges from 25 per hour to 200+ per hour

Capacity of Aprons

- Often a tough problem!
- Different stands can accommodate different sizes of aircraft
- Remote vs. contact stands
- Shared use vs. exclusive use (airlines, handlers)
- Dependences among stands
- Static capacity: No. of aircraft that can be parked simultaneously at the stands. (Easy!)
- Dynamic capacity: No. of aircraft that can be accommodated per hour. (Can be difficult to compute.)

Stand Blocking Time (SBT)

- Scheduled occupancy time (SOT) [20 mins – 4 hours, excepting overnights]
- Positioning time (PT) [3 – 10 mins]
- Buffer time (BT) [up to 1+ hour at some locations]

$$SBT = SOT + PT + BT$$

A Simple Case

- Assume *n* stands; all can accommodate all aircraft sizes
- Subdivide aircraft into *K* relatively homogeneous classes w.r.t. *SBT*

$$E[SBT] = \sum_{i=1}^{K} p_i \cdot SBT_i$$

- Dynamic capacity = *n* / *E*[*SBT*]