Airfield Capacity

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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
  - $\mu = \text{maximum throughput rate}$
  - $E(t) = \text{expected service time}$
  - $\mu = \frac{1}{E(t)}$

- **Level of Service (LOS) related capacity**
  - Number of demands processed per unit of time while meeting some pre-specified LOS standards (must know $\mu$ 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
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): $255000 \, \text{lbs} < \text{MTOW}$
  - Large (L): $41000 \, \text{lbs} < \text{MTOW} < 255000 \, \text{lbs}$
  - Small (S): $\text{MTOW} < 41000 \, \text{lbs}$
- 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):

<table>
<thead>
<tr>
<th>Leading aircraft</th>
<th>H</th>
<th>L or B757</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>4</td>
<td>5</td>
<td>5/6*</td>
</tr>
<tr>
<td>B757</td>
<td>4</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>L</td>
<td>2.5 (or 3)</td>
<td>2.5 (or 3)</td>
<td>3/4*</td>
</tr>
<tr>
<td>S</td>
<td>2.5 (or 3)</td>
<td>2.5 (or 3)</td>
<td>2.5 (or 3)</td>
</tr>
</tbody>
</table>

* 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)

<table>
<thead>
<tr>
<th>Leading aircraft</th>
<th>H</th>
<th>L + B757</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>90</td>
<td>120</td>
<td>120</td>
</tr>
<tr>
<td>B757</td>
<td>90</td>
<td>120</td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>60</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>S</td>
<td>45</td>
<td>45</td>
<td>45</td>
</tr>
</tbody>
</table>

### 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)

\[
\begin{bmatrix}
H & M/L & S \\
5 & 5 & 7 \\
5 & 5 & 5 \\
5 & 5 & 5 \\
\end{bmatrix}
\]

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

<table>
<thead>
<tr>
<th>Separation between runway centerlines</th>
<th>Arrival/arrival</th>
<th>Departure/departure</th>
<th>Arrival/departure</th>
<th>Departure/arrival</th>
</tr>
</thead>
<tbody>
<tr>
<td>700-2499 ft</td>
<td>As in single runway</td>
<td>As in single runway</td>
<td>Arrival touches down</td>
<td>Departure is clear of runway</td>
</tr>
<tr>
<td>2500-4300 ft</td>
<td>1.5 nmi (diagonal)</td>
<td>Indep’nt</td>
<td>Indep’nt</td>
<td>Indep’nt</td>
</tr>
<tr>
<td>4,300 ft or more</td>
<td>Indep’nt</td>
<td>Indep’nt</td>
<td>Indep’nt</td>
<td>Indep’nt</td>
</tr>
</tbody>
</table>
The diagonal separation between two aircraft approaching medium-spaced parallel runways

\[ S_{ij} = 1.5 \text{ n. mi.} \]

\[ d \quad [2,500 \text{ ft.} \leq d < 4,300 \text{ ft.}] \]

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

<table>
<thead>
<tr>
<th>Weather Category</th>
<th>Spring</th>
<th>Summer</th>
<th>Fall</th>
<th>Winter</th>
<th>Annual</th>
</tr>
</thead>
<tbody>
<tr>
<td>VFR1</td>
<td>79.19</td>
<td>78.78</td>
<td>80.03</td>
<td>77.94</td>
<td>78.99</td>
</tr>
<tr>
<td>VFR2 / IFR1</td>
<td>10.26</td>
<td>13.86</td>
<td>11.73</td>
<td>12.42</td>
<td>12.07</td>
</tr>
<tr>
<td>IFR2</td>
<td>7.95</td>
<td>5.83</td>
<td>6.43</td>
<td>6.89</td>
<td>6.78</td>
</tr>
<tr>
<td>IFR3</td>
<td>.08</td>
<td>.08</td>
<td>.19</td>
<td>.02</td>
<td>.09</td>
</tr>
<tr>
<td>IFR4</td>
<td>2.50</td>
<td>1.45</td>
<td>1.63</td>
<td>2.80</td>
<td>2.07</td>
</tr>
</tbody>
</table>
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 $i, j$
   
   \[ t_{ij} = \text{average time interval between successive movements of a pair of aircraft of types } i \text{ and } j \text{ (}i\text{ followed by } j\text{) such that no ATC separation requirements are violated} \]

2. Compute probability for all $i, j$
   
   \[ p_{ij} = \text{probability of occurrence of the pair of aircraft types } i \text{ and } j \text{ (}i\text{ followed by } j\text{)} \]

3. Compute overall average service time
   
   \[ E(t) = \sum_i \sum_j p_{ij} \cdot t_{ij} \]
   
   \[ \mu = \frac{1}{E(t)} \]

Numerical Example

Given: Single Runway (Arrivals Only: IFR)

\[ n = 5 \text{ N. Miles} \]

<table>
<thead>
<tr>
<th>Aircraft Types</th>
<th>Type</th>
<th>Mix (%)</th>
<th>Approach Speed (kts)</th>
<th>Runway Occupancy Time (secs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heavy (1)</td>
<td>20</td>
<td>140</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td>Large (2)</td>
<td>50</td>
<td>120</td>
<td>55</td>
<td></td>
</tr>
<tr>
<td>Small (3)</td>
<td>30</td>
<td>100</td>
<td>50</td>
<td></td>
</tr>
</tbody>
</table>

\[ S_{ij} = \begin{bmatrix} 1 & 2 & 3 \\ 1 & 4 & 5 \ast \\ 2 & 3 & 3 \ast \\ 3 & 3 & 3 \ast \end{bmatrix} \]

\* 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

ในช่วงClosing Case(153,226),(636,301)
- 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(153,379),(750,453)
- 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**

$$ T_{12} = \max \left\{ \frac{10 \text{ n.mi.}}{120 \text{ knots}}, \frac{5 \text{ n.mi.}}{140 \text{ knots}}, 60 \text{ sec} \right\} = \max (71 \text{ sec}, 60 \text{ sec}) = 171 \text{ sec} $$

- **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 $T_{23}$)**

$$ T_{13} = \max \left\{ \frac{6 \text{ n.mi.}}{100 \text{ knots}}, 60 \text{ sec} \right\} = \max (216 \text{ sec}, 60 \text{ sec}) = 216 \text{ sec} $$

Matrix of Minimum Separations [2]
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 $j$.

\[ t_{ij} = T_{ij} + b \]

\[
\begin{bmatrix}
113 & 181 & 226 \\
87 & 100 & 154 \\
87 & 100 & 118 \\
\end{bmatrix}
\]
Matrix of Pair Probabilities

Let $p_{ij} = \text{probability that an aircraft of type } i \text{ will be followed by one of type } j$

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:

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

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

\[
[p_{ij}] = \begin{bmatrix}
0.04 & 0.1 & 0.06 \\
0.1 & 0.25 & 0.15 \\
0.06 & 0.15 & 0.09
\end{bmatrix}
\]
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:  
\[ E(t) = \sum_{i} \sum_{j} p_{ij} \cdot t_{ij} \]

Numerically:
\[ E(t) = (0.04)(113) + (0.1)(181) + (0.06)(226) + (0.1)(87) + (0.25)(100) + (0.15)(154) + (0.06)(87) + (0.15)(100) + (0.09)(118) \]

That is:  
\[ E(t) = 124 \text{ seconds} \]

Saturation Capacity  
\[ \frac{3600 \text{ seconds}}{124 \text{ seconds}} = 29 \text{ aircraft} \]

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

Runway Configuration Capacity Envelopes
(Source: ETMS / Tower Records, 7-9 AM, 4-8 PM, July 1-15 1998 except Saturdays, Logan Airport)

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: None 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

```
Number of movements per hour

<table>
<thead>
<tr>
<th>%</th>
<th>0</th>
<th>20</th>
<th>40</th>
<th>60</th>
<th>80</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>12</td>
<td>15</td>
<td>18</td>
<td>21</td>
<td>24</td>
<td>27</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>3a</td>
<td>16</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
```

Percent of time (%)
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 = \( n / E[SBT] \)