The two most commonly used sources of geometric specifications for airfield design are:

1. ICAO Annex 14 (“Aerodromes”) and associated supplements and manuals
2. FAA Advisory Circular 150/5300-13 (“Airport Design”)


FAA updates of specifications are usually developed earlier than updates to ICAO Annex 14 (e.g., Group VI standards)

Reference: de Neufville and Odoni, Ch. 9, Secs. 2-3, 5-9
Classification (FAA)

Aircraft Approach Category

- **A:** Speed < 91 knots
- **B:** [ 91 - 121) knots
- **C:** [ 121 - 141) knots
- **D:** [ 141 - 166) knots
- **E:** Speed 166+ knots

Airplane Design Group

- **I:** Wing < 49 ft (15 m)
- **II:** [ 49 - 79) ft (15-24 m)
- **III:** [ 79 - 118) ft (24-36 m)
- **IV:** [ 118 - 171) ft (36-52 m)
- **V:** [ 171 - 214) ft (52-65 m)
- **VI:** [ 214 - 262) ft (65-80 m)

Airport Reference Codes (ICAO)

<table>
<thead>
<tr>
<th>Code #</th>
<th>Reference field length</th>
<th>Code letter</th>
<th>Wing span</th>
<th>Main gear wheel span</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Up to 800 m</td>
<td>A</td>
<td>Up to 15 m</td>
<td>Up to 4.5 m</td>
</tr>
<tr>
<td>2</td>
<td>800-1200 m</td>
<td>B</td>
<td>15 – 24 m</td>
<td>4.5 – 6 m</td>
</tr>
<tr>
<td>3</td>
<td>1200-1800 m</td>
<td>C</td>
<td>24 – 36 m</td>
<td>6 – 9 m</td>
</tr>
<tr>
<td>4</td>
<td>1800 m +</td>
<td>D</td>
<td>36 – 52 m</td>
<td>9 – 14 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>E</td>
<td>52 – 65 m</td>
<td>9 –14 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>F</td>
<td>65 – 80 m</td>
<td>14 –16 m</td>
</tr>
</tbody>
</table>
Remarks re ICAO and FAA Airport Reference Codes

- Practically all major commercial airports belong to the ICAO Code #4 class
- Main gear wheel span (ICAO) is “dominated” by wing span
- ICAO Code Letters A-F wing spans correspond exactly to FAA Airplane Design Groups I-VI wing spans
- Most geometric specifications for airports are determined by the wing span of the most demanding aircraft
A380 vs. B747

Airbus A380
- Wingspan: 261.7 feet (79.8 m)
- Length: 239.3 feet (72.2 m)
- Height: 79.6 feet (24.1 m)
- Max Takedoff Weight: 1,235 million pounds (560 tons)
- Seats: 555-653
- Max Fuel Capacity: 81,890 gallons

Boeing 747-400:
- Wingspan: 211.4 feet (64.4 m)
- Length: 231.8 feet (70.8 m)
- Height: 63.7 feet (19.4 m)
- Max Takeoff Weight: 875,000 pounds (396 tons)
- Seats: 416-660
- Max Fuel Capacity: 57,285 gallons

Runway Separations (FAA)*

<table>
<thead>
<tr>
<th>Runway Centerline To...</th>
<th>AIRPLANE DESIGN GROUP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>I</td>
</tr>
<tr>
<td></td>
<td>Hold Line</td>
</tr>
<tr>
<td></td>
<td>250 ft</td>
</tr>
<tr>
<td></td>
<td>75 m</td>
</tr>
<tr>
<td></td>
<td>250 ft</td>
</tr>
<tr>
<td></td>
<td>75 m</td>
</tr>
<tr>
<td></td>
<td>250 ft</td>
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<td>75 m</td>
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<td>250 ft</td>
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<td></td>
<td>75 m</td>
</tr>
<tr>
<td></td>
<td>250 ft</td>
</tr>
<tr>
<td></td>
<td>75 m</td>
</tr>
</tbody>
</table>

*For aircraft approach Cat. C and D
Airfield Capacity

Amedeo R. Odoni
Massachusetts Institute of Technology

Airfield Capacity: I

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

Reference: Chapter 10
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)

Definitions: Runway Capacity*

- **Maximum Throughput (or Saturation) Capacity**
  The expected ("average") number of runway operations (takeoffs and landings) that can be performed in one hour without violating ATC rules, assuming continuous aircraft demand.

- **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; no generally accepted LOS; typically set to about 85-90% of saturation capacity; may be affected by apron capacity and terminal capacity

* These definitions can be applied to a single runway or to the entire complex of runways at an airport.
**LOS-Related Capacity Definitions (Less Common)**

- **Practical Hourly Capacity**
  The average number of operations that can be performed in one hour on a runway (or, more generally, a system of active runways) with an average delay per operation of 4 minutes.

- **Sustained Capacity**
  The average number of operations per hour that can be “sustained” for periods of several hours; vaguely-defined, typically workload-related.

---

**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 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”
### 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**

---

### Departure-Departure (approximate, in seconds)

<table>
<thead>
<tr>
<th>Leading aircraft</th>
<th>Trailing aircraft</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>H</td>
</tr>
<tr>
<td>H</td>
<td>90</td>
</tr>
<tr>
<td>B757</td>
<td>90</td>
</tr>
<tr>
<td>L</td>
<td>60</td>
</tr>
<tr>
<td>S</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; except Rome, Milan)

Arrival/Arrival (in nautical miles)
\[
\begin{bmatrix}
H & 5 & 5 & 7 \\
M/L & 5 & 5 & 5 \\
S & 5 & 5 & 5
\end{bmatrix}
\]

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>
Diagonal separation: medium-spaced parallel runways

Aircraft $i$

$S_{ij} = 1.5 \text{ n. mi.}$

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

Aircraft $j$

Staggered parallels: arrivals on “near” runway

“offset”

arrivals runway

“near end”

departures runway

“far end”
High-capacity configurations in opposite directions, Boston/Logan (VMC)

Old low-capacity configuration in VMC, Boston Logan
**Configurations: Same Direction, Different Weather Conditions**

**LIFR**
- B, C, D
- 4R
- A, B1, B2
- B, C, D

**VFR**
- A, B1, B2
- 4L
- 4R
- 09
- B3, C1, D1
- B3, C2, D2

---

**Typical Approach for Estimating Runway Capacity**

1. Compute average time interval for all possible aircraft class pairs i, j
   
   \[ t_{ij} = \text{average time interval between successive movements of a pair of aircraft of types } i \text{ and } j \text{ (i followed by j) such that no ATC separation requirements are violated} \]

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

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

Given: Single Runway
(Arrivals Only: IFR)
n = 5 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>Type</td>
<td>Mix</td>
<td>Speed</td>
<td>Occupancy</td>
<td>Time</td>
</tr>
<tr>
<td>Heavy (1)</td>
<td>20</td>
<td>140</td>
<td></td>
<td>60</td>
</tr>
<tr>
<td>Large (2)</td>
<td>50</td>
<td>120</td>
<td></td>
<td>55</td>
</tr>
<tr>
<td>Small (3)</td>
<td>30</td>
<td>100</td>
<td></td>
<td>50</td>
</tr>
</tbody>
</table>

\[
[S_{ij}] = \begin{bmatrix}
1 & 2 & 3 \\
1 & 4 & 5 & 6^* \\
2 & 3 & 4^* \\
3 & 3 & 3 & \end{bmatrix}
\]

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

Arrival Capacity Model of a Single Runway

- Idealized representation:
  - n: length of final approach path
  - i (j): type [heavy/large/medium/small] of leading (trailing) aircraft
  - \(v_i\): ground speed of type i aircraft
  - \(o_i\): runway occupancy time of type i aircraft
  - \(s_{ij}\): minimum longitudinal separation between two airborne aircraft
  - \(T_{ij}\): minimum acceptable time interval between successive arrivals at the runway of type i and type j aircraft (unknown)
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 area (beginning of final approach) is greater than minimum

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

Minimum Time Separation of Two Aircraft

- Minimum time separation is a consequence of:
  - Only a single aircraft can be on the runway at a given time instant
  - Minimum longitudinal separation must not be violated

Question: What is the expression for the minimum time separation $T_{ij}$?

Answer:

$$T_{ij} = \max \left[ \frac{n + s_{ij}}{v_j} - \frac{n}{v_j}, o_i \right] \quad \text{for } v_i > v_j \quad \text{('opening case')}$$

$$T_{ij} = \max \left[ \frac{s_{ij}}{v_j}, o_i \right] \quad \text{for } v_i \leq v_j \quad \text{('closing case')}$$
Graphical Description of the Model

- ‘opening case’: $v_i > v_j$
- ‘closing case’: $v_i \leq v_j$

Minimum Acceptable Average Inter-arrival Time

$$T_{ij} = \begin{cases} 
\max \left[ n + \frac{s_{ij}}{v_j} - \frac{n}{v_i}, o_i \right] & \text{for } v_i > v_j \text{ (‘opening case’)} \\
\max \left[ \frac{s_{ij}}{v_j}, o_i \right] & \text{for } v_i \leq v_j \text{ (‘closing case’)}
\end{cases}$$

- $K$: number of aircraft types
- Number of ‘type $i$ aircraft followed by type $j$ aircraft’ pairs: $K^2$
- $p_{ij}$: probability of ‘type $i$ aircraft followed by type $j$ aircraft’ pair
- Minimum acceptable inter-arrival time: $E[T_{ij}] = \sum_{i=1}^{K} \sum_{j=1}^{K} p_{ij} \times T_{ij}$
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

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

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

- Closing Case

\[
T_{33} = \max \left( \frac{3 \text{ n.mi.}}{140 \text{ knots}}, 50 \text{ sec} \right)
\]

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

- Stable Case

\[
T_{23} = \max \left( \frac{3 \text{ n.mi.}}{120 \text{ knots}}, 55 \text{ sec} \right)
\]

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

- “Special” Case (also \( T_{23} \))

\[
T_{33} = \max \left( \frac{6 \text{ n.mi.}}{100 \text{ knots}}, 60 \text{ sec} \right)
\]

\[
= \max(216 \text{ sec}, 60 \text{ sec}) = 216 \text{ sec}
\]
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 \( \frac{1}{3} \) n. mi. longitudinal separation).

Matrix of Average Time Separations

The \( t_{ij} \) indicate 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 $p_{ij} = \text{probability that an aircraft of type } i \text{ will be followed by one of type } j$

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 valid only for a 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 at the runway in question.

That is:

\[
E(t) = \sum_{i} \sum_{j} p_{ij} \cdot t_{ij}
\]

Numerically:

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

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

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

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,

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

The standard deviation, \(\sigma_t = \sqrt{1542} = 39 \text{ seconds}\)
Sensitivity of the model

- The model (and the runway’s arrival capacity) is sensitive to
  - Airborne separation requirements (regular and wake-turbulence related)
  - Runway occupancy times
  - Final approach speeds of aircraft
  - Length of final approach
  - Safety-related margins (buffers) allowed by air traffic controllers
  - Mix of traffic (homogeneity)
  - Sequencing of aircraft

Typical capacity envelope for a single runway

![Diagram showing typical capacity envelope for a single runway with axes for arrivals/hour and departures/hour, and a feasible region marked with points labeled 1, 2, and 3. The 45° line indicates the boundary of the feasible region.](image-url)
Capacity envelope: strings of arrivals and departures

Capacity envelope: two parallel runways, one for arrivals, the other for departures
Hypothetical capacity envelope for a multi-runway airport with mixed use of runways

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

Annual Capacity Coverage Chart: Boston/Logan

![Chart showing movements per hour vs % of time](image)

Page 47

Page 48
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.
Airfield Capacity: II

Objective
– To summarize fundamental concepts re. airfield capacity

Topics
– Capacities of other elements of the airfield
– Overall observations about capacities of airports

Reference: Chapter 10

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
Runway Capacity: US and Elsewhere

  - 26 of 35: VMC capacity > 100/hour; range: 56 – 279
  - 16 of 35: IMC capacity > 100/hour; range: 48 – 193
  - 12 of 35: Plan new runway by 2010; capacity benefits of 20 – 50%, with exceptions
  - Capacity benefits due to ATM: small (0–10%) except for some cases (e.g., SFO)

- Only three non-US airports have a declared capacity of more than 100/hour (!) – 4 (?) more within next 5-10 years

- 16 major European airports (including practically all the busiest ones) received more requests for slots than they could handle for summer of 2007

- Slot coordination system “hides” problem outside the US

Capacity of Taxiways

- The capacity of the taxiway system is rarely, if ever, the capacity bottleneck of major airports

- However, some specific parts of the taxiway system may consistently act as “hot spots” (points of congestion), especially at older, limited-area airports

- Local geometry and traffic flows determine the location of these hot spots

- The blocking of groups of stands by a single lane passage is one of the most common examples of such taxiway hot spots
Single lane vs. dual lane access to stands

Single Lane Width
- Taxilane object free area
- 1.2 span + 20 ft. (6m)
- Service road

Dual Lane Width
- Taxilane object free area
- 2.3 span + 30 ft. (9m)
- Service road
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)
- Dependence among neighboring 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 minutes to 4 hours, except for overnight stays]
- 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 = \( n / E[SBT] \)