ASSESSMENT OF RUNWAY CAPACITY FOR SHANGHAI PUDONG INTERNATIONAL AIRPORT

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Abstract: This paper gives a basically theoretically analytical model of the ultimate capacity of two parallel runways. The capacity model is about two operation modes of runways, one is absolutely independent operation mode, and another is dependent approach and independent departure mode. Apply the capacity mode to estimating the ultimate capacity of Shanghai Pudong International Airport two runways system. Also compare the runways capacity curve of two operation mode. The result of this analysis shows that the capacity model works effectively with the degree of accuracy in the assessment of airport runway capacity.

Key Words: Capacity model, Independent operation, Dependent approach

1. INTRODUCTION

As known, assessment of airport capacity is one of pivotal technology of air traffic management, for runway capacity is the most important decisive factor to airport capacity. In the process of assessment airport capacity, runways as the most tend to bottleneck of airport subsystem decide the level of whole airport capacity (HU et al, 2000). Early, the study of airport capacity focuses on single runway capacity, but with the traffic flow increasing, adopting multiple runways system (such as parallel runways) to break the capacity bottleneck is the inevitable trend for airport construction. This paper studies two parallel runways system of Shanghai Pudong airport and estimates it’s the runways capacity. Also adopts actual operation data of the airport to validate the model of capacity assessment.

The capacity model of this paper is analytical model. The model uses finite parameters of having important influence on the object of assessment to estimate runways capacity. The important parameters of runways capacity contain separation al standard, final approach speed, runway occupancy time and aircraft types and so on. The airport runway ultimate capacity is usually expressed as the maximum number of aircraft accommodated under conditions of constant demand for service. The runways capacity equals to the reciprocal of the average service time.
2. SHANGHAI PUDONG INTERNATIONAL AIRPORT RUNWAYS SYSTEM

Shanghai Pudong international airport runways system belongs to parallel runways system. Respectively eastern and western runway and the separation of the two runways is 2260m. So the landing aircraft can perform independent parallel approach, but the airport doesn’t adopt the operation of independent parallel approach. For giving reference to manager, this paper uses two mode of operation respectively to estimate the runways capacity of the airport. One of the modes is independent parallel approach and independent departure; another is dependent parallel approach and independent departure.

The arrival and departure aircrafts in Shanghai Pudong airport mainly belong to large and heavy. The small craft is very few, so can be ignored. The Boeing757 belong to large aircraft, its wake-vortex is similar to heavy aircraft, so regard Boeing757 as heavy aircraft. Accordingly, in the study of capacity assessment, adopt simply the ATC minimum longitudinal wake-vortex separation rules under radar control.

<table>
<thead>
<tr>
<th>trailing</th>
<th>leading</th>
<th>Heavy</th>
<th>Large</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heavy</td>
<td>8km</td>
<td>6km</td>
<td></td>
</tr>
<tr>
<td>Large</td>
<td>10km</td>
<td>6km</td>
<td></td>
</tr>
</tbody>
</table>

3. INDEPENDENT OPERATION CAPACITY MODEL OF PUDONG AIRPORT TWO RUNWAYS

In the case of independent operation, the relation between arriving and departing traffic flows concretely is: the arriving flows of eastern runway are independent with the arriving flows of western runway; the arriving flows of eastern runway are independent with the departing flows of western runway; the departing flows of eastern runway are independent with the arriving flows of western runway; the departing flows of eastern runway are independent with the departing flows of western runway; the arriving and departing flows are dependent with each other in the same runway. So the every single runways capacity of two runways system is theoretically equal and the capacity of two runways system is twice the single runway capacity. CHEN (2004), JIANG et al (2003) and Antonio et al (2003) have developed the single runway capacity model in detail, so in this paper don’t develop again, just simply introduces as follows.

3.1 The Model for Arrivals
Successive landings on single runway show in Figure 1.

![Figure 1 Successive landing on single runway](image-url)
According to the speed of arriving aircraft, there are two following cases:

1). Trailing aircraft is faster than leading aircraft \((v_j > v_I)\)

In this case, the separation of two successive aircraft reduces bit by bit in the process of the final approach. The minimum longitudinal separation \(\delta_{IJ}\) happens at the threshold of runway for aircraft sequence \(IJ\). Thereby, the minimum inter-arrival time \(a_{IJ}^{t}\) of the aircraft sequence \(IJ\) can be showed as follows, considering the buffer time \(B_{IJ}\).

\[
a_{IJ}^{t} = \max\left(\frac{\delta_{IJ}}{v_j} + B_{IJ}, r_I\right)
\]

(1)

Where \(B_{IJ} = \sigma_{0}\Phi^{-1}(q_e)\) and \(r_I = \overline{ROT}_I + \sqrt{\sigma_0^2 + \sigma_r^2} \Phi^{-1}(q_e)\)

where, \(\sigma_0\) is standard deviation of Position Delivery Error, \(\sigma_r\) is standard deviation of aircraft runway occupancy time, \(\overline{ROT}_I\) is average runway occupancy time of arriving aircraft, \(r_I\) is the runway occupancy time of arriving aircraft while considering buffer time, \(q_e\) is the probability of non-violation of the minimum separation criteria between two aircraft.

2). Leading aircraft is faster than trailing aircraft \((v_I \geq v_j)\)

In this case the separation between the two aircraft will be increasing during the final approach. Thus, the critical point is at the beginning of the final approach path. Specifically, at the time of trailing aircraft enters the threshold of final approach, the separation between the two aircraft couldn’t less than minimum longitudinal separation \(\delta_{IJ}\). Thereby, the minimum inter-arrival time \(a_{IJ}^{t}\) of the aircraft sequence \(IJ\) can be showed as follows, considering the buffer time \(B_{IJ}\).

\[
a_{IJ}^{t} = \max\left(\frac{\delta_{IJ}}{v_j} + \frac{1}{v_I} - 1 + B_{IJ}, r_I\right)
\]

(2)

\[
B_{IJ} = \sigma_{0}\Phi^{-1}(q_e) - \delta_{IJ}\left(\frac{1}{v_I} - \frac{1}{v_j}\right)
\]

(3)

where, \(B_{IJ} = 0\) if \(B_{IJ} < 0\).

Then the expected inter-arrival time can be computed as:

\[
\tilde{t} = \sum_{IJ} a_{IJ}^{t} \cdot p_i \cdot p_j
\]

(4)

where, \(p_i\) , \(p_j\) is the proportion of types \(I, J\) in the mix, respectively.

The arrival capacity of single runway can be computed as:

\[
C_A = 1/\tilde{t}
\]

(5)

### 3.2 The Model for Departures

Generally, the successive departures can be carried out according to the ATC minimum rules respecting their wake-vortex rules and securing that no more than one aircraft occupy the runway during any time. Thereby, the minimum inter-departure time \(d_{IJ}^{t}\) between departing aircrafts \(I, J\) can be computed as follows, and consider buffer time.

\[
d_{IJ}^{t} = \max\left(\frac{d_{IJ}^{t}}{v_j} + B_{IJ}, d_j\right)
\]

(6)

\[
B_{IJ} = \sigma_{0}\Phi^{-1}(q_e)
\]

(7)
\[
d_{ij} = \overline{R}_j + \left(\sigma_0^2 + \sigma_k^2\right)\Phi^{-1}(q_e)
\]

Where, \(d_{IJ/\text{min}}\) is the ATC minimum time-based separation rules between successive departing aircraft types \(I\) and \(J\). \(\overline{R}_j\) is the average runway occupancy time for departing aircraft, \(d_{ij}\) is the runway occupancy time for departing aircraft by considering buffer time.

Then the expected inter-departure time can be computed as:
\[
t_{d} = \frac{\sum_{IJ} p_{ij} \cdot t_{d_{IJ}}}{p_{ij}}.
\]

The departure capacity of single runway can be computed as:
\[
C_{D} = \frac{1}{t_{d}}
\]

### 3.3 The Model for Mixed Operations

A single departure might be inserted between successive arrivals \(IJ\). Leading aircraft \(I\) must clear away from the runway after landing and the arrival \(J\) should be no closer than the prescribed minimum ATC separation rules \(\delta\) from the threshold of runway. The following condition making realization of \(n\) departures between the arrival sequences \(IJ\), the inter-arrival time of arrival sequence \(IJ\) can be computed as:
\[
a_{t_{IJ}} = r_i + (n-1)d_{t_{IJ}} + \frac{\delta_{\text{EJ}}}{v_j} + \sigma_{r}\Phi^{-1}(q_e)
\]

The expected service time can be computed as:
\[
\overline{t} = E[a_{t_{IJ}}] = E[r_i] + E[(n-1)d_{t_{IJ}}] + E[\frac{\delta_{\text{EJ}}}{v_j}] + \sigma_{r}\Phi^{-1}(q_e)
\]

The capacity of single runway for the mixed operations can be computed as:
\[
C^* = 1/\overline{t} (1+\sum_{n=1}^{N} np_n)
\]

Where, \(p_n\) is the probability of realizing \(n\) departures between the arriving sequences \(IJ\).

### 4. THE CAPACITY MODEL FOR PUDONG TWO DEPENDENT PARALLEL RUNWAYS

The two parallel runways in Pudong international airport is far spaced parallel runways. Because of ATC technology isn’t too perfect to insure the runways system absolutely independent operation at any time, the runways system could operate under the mode of dependent arrival and independent departure [2]. The relation between arriving and departing traffic flows concretely is: the arriving flows of eastern runway are dependent with the arriving flows of western runway; the arriving flows of eastern runway are independent with the departing flows of western runway; the departing flows of eastern runway are dependent with the arriving flows of western runway; the departing flows of eastern runway are dependent with the departing flows of western runway; the arriving and departing flows is dependent with each other in the same runway.

#### 4.1 The Model for Arrivals

(Milan, 2006)

Figure 2 illustrates the basic geometry of the dual parallel runways and “string” of three landing aircraft in the horizontal plane. The aircraft \(I\) and \(J\) follow the final approach path from the entry gate \(E_i\) to the landing threshold \(T_i\) of runway RWY1 and the aircraft
K follows the final approach path from the entry gate $E_2$ to the landing threshold $T_2$ of runway RWY2 in the order $I - K - J$.

Figure 2 Geometry of landing on dual dependent parallel runways

Analyzing the figure 2, the aircraft “string” $I - K - J$ must be separated as follows: Sequence $IJ$ ($I$ is leading and $J$ is trailing aircraft) satisfying the ATC longitudinal separation rules; and sequence $IK, KJ$ satisfying the ATC lateral-diagonal separation rules.

As in the analytical models of single runway, let $a_{IJ/K}$ be the inter-arrival time between the aircraft $I$ and $J$ at the threshold $T_1$ of RWY1 as depend on the aircraft $K$ landing at the threshold $T_2$ of RWY2. The time $a_{IK}$ and $a_{KJ}$ is the inter-arrival time between the aircraft $I$ and $K$ at their landing threshold $T_1$ and $T_2$, respectively; and $a_{KJ}$ is the inter-arrival time between the aircraft $K$ and $J$ at their landing threshold $T_2$ and $T_1$, respectively. Considering the runway occupancy time, so $a_{IJ/K}$ can be computed as:

$$a_{IJ/K} = \max(r_i, a_{IK}) + \max(r_k, a_{KJ})$$

(14)

Where, $r_i, r_k$ is aircraft $I$ and $K$ runway occupancy time.

Considering the buffer time, $a_{IK}$ and $a_{KJ}$ can be computed as:

$$a_{IK} = \frac{S_{IK} + \gamma_2}{v_I} - \frac{\gamma_1}{v_I} + \sigma_0 \Phi^{-1}(q_v)$$

(15)

$$a_{KJ} = \frac{S_{IK} + S_{KJ} + \gamma_1}{v_J} - \frac{S_{IK} + \gamma_2}{v_K} + \sigma_0 \Phi^{-1}(q_v)$$

(16)

Where, $\gamma_1, \gamma_2$ is length of the final approach path of the runway RWY1 and RWY2, respectively. $v_I, v_J, v_K$ is the average approach speed of the aircraft $I, J$ and $K$, respectively. $\delta_{ij}$ is the ATC minimum longitudinal separation rule applied to aircraft sequence $IJ$. $S_{IK}, S_{KJ}$ is the separation between the aircraft sequence $IK$ and $KJ$, respectively, when the aircraft $I$ is on the gate $E_1$ of RWY1.

In addition to the ATC separation rules applied to the aircraft of different wake-vortex categories, $S_{IK}, S_{KJ}$ is the subject of combinations of different types $I, K$ and $J$ in terms of the final approach speed. In general, the relative speed between two aircraft can either be “fast”-F or “slow”-S. This gives eight possible combinations of three aircraft in the “string” $IKJ$. In the first four combinations, the aircraft $I$ and $J$ are considered as either “slow” or “fast” and the aircraft $K$ as “slow”, i.e., $S - s - S, S - s - F, F - s - S$ and
In the next four combinations, the aircraft $K$ is considered as “fast”, i.e., $S - f - S, S - f - F, F - f - S$ and $F - f - F$.

Consequently, after setting $a_{IK} = \frac{S_{IK/\min}}{v_K}$ and $a_{KJ} = \frac{S_{KJ/\min}}{v_J}$ for the sequences $v_j < v_K$ and $v_K < v_J$, respectively, and $S_{IK} = S_{IK/\min}$ and $S_{KJ} = S_{KJ/\min}$ for the sequences $v_j \geq v_K$ and $v_K \geq v_J$, respectively, the separation $S_{IK}$ and $S_{KJ}$ are determined as:

1. $S_{IK} = S_{IK/\min} + \gamma_1(\frac{v_j}{v_K}) - \gamma_2$ and $S_{KJ} = S_{KJ/\min}$, $v_j < v_K \geq v_J$
2. $S_{IK} = S_{IK/\min}$ and $S_{KJ} = S_{KJ/\min} + S_{IK/\min}(v_j/v_K - 1) + \gamma_2(\frac{v_j}{v_K}) - \gamma_1$, $v_j \geq v_K < v_J$
3. $S_{IK} = S_{IK/\min}$ and $S_{KJ} = S_{KJ/\min}$, $v_j \geq v_K \geq v_J$
4. $S_{IK/\min} = \max(\delta_{IK}, \sqrt{\rho_{IK}^2 + D^2})$
5. $S_{KJ/\min} = \max(\delta_{KJ}, \sqrt{\rho_{KJ}^2 + D^2})$

Where $S_{IK/\min}, S_{KJ/\min}$ is the minimum separation between the aircraft $IK$ and $KJ$, respectively. $\rho_{IK}, \rho_{KJ}$ is the ATC minimum lateral-diagonal separation rules applied to the successive sequence $IK$ and $KJ$. $D$ is the separation between the parallel runways centerlines.

Then the expected inter-arrival time can be computed as:

$$\bar{t} = \sum_{IJK} a_{IJK} P_I P_J P_K.$$  \hspace{1cm} (17)

The arrival capacity of dependent two parallel runways can be computed as:

$$C_A = 2/\bar{t}.$$  \hspace{1cm} (18)

### 4.2 The Model for Departures

In the case of the operation, the departure operation is independent. So, the departure capacity of two parallel runways is equal to the summation of every single runway capacity. The single capacity model is the same to section 3.2.

### 4.3 The Model for Mixed Operation

In the case of dependent approach and independent departure, departures might be inserted between successive arrivals $IK$ and $KJ$. Because of the arriving flows of eastern runway are independent with the departing flows of western runway; the departing flows of eastern runway are independent with the arriving flows of western runway; the departing flows of eastern runway are independent with the departing flows of western runway; just only the arriving and departing flows are dependent with each other in the same runway. Thereby, inserted departures shouldn’t consider the influence of arrivals and departures in another runway, but must observe the minimum ATC separation rules between departure and arrival. Thus, the two parallel runways capacity of mixed operation is also equal to the summation of every single runway capacity. The single capacity model for mixed operation is the same to section 3.3.
5. CAPACITY CURVE OF PUDONG INTERNATIONAL AIRPORT RUNWAYS

According to the statistical operation data provided by the Eastern ATC, use these model to estimating the capacity of Pudong International Airport Runways. The basic data of the airport are: the separation $D = 2260m$ between the runway centerlines; the length of the final approach path, eastern runway $\lambda_1 = 11.11km$, western runway $\lambda_2 = 16.83km$; the ATC minimum lateral-diagonal separation rules is $\rho = 4km$; the ATC minimum separation rules between successive arrivals with different wake-vortex categories are given in Table1; aircraft classification are given in Table2; the ATC minimum separation rules between successive departures with different wake-vortex categories are given in Table3; the probability of non-violation of the minimum separation criteria between two aircraft is $q_v = 0.95$; standard deviation of Position Delivery Error is $\sigma_0 = 20s$; standard deviation of aircraft runway occupancy time is $\sigma_R = 15s$.

<table>
<thead>
<tr>
<th>Type</th>
<th>Proportion in the mix</th>
<th>Average approach speed</th>
<th>Runway (landing) occupancy time (s)</th>
<th>Runway (departing) occupancy time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heavy</td>
<td>38%</td>
<td>270km/h</td>
<td>45</td>
<td>30</td>
</tr>
<tr>
<td>Large</td>
<td>62%</td>
<td>240km/h</td>
<td>38</td>
<td>28</td>
</tr>
</tbody>
</table>

Table 3 The ATC Minimum Separation rules between successive Departures of different wake-vortex categories

<table>
<thead>
<tr>
<th>Aircraft sequence</th>
<th>Heavy</th>
<th>Large</th>
</tr>
</thead>
<tbody>
<tr>
<td>I/J</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heavy</td>
<td>120</td>
<td>120</td>
</tr>
<tr>
<td>Large</td>
<td>90</td>
<td>90</td>
</tr>
</tbody>
</table>

The basic results are shown as:

The case of independent operation of Pudong airport two parallel runways system are: the max arrival capacity is 48ops/h; the max departure capacity is 52ops/h; the capacity of arrivals and departure by turns is 64ops/h.

The case of dependent approach and independent departure of Pudong airport two parallel runways system: the max arrival capacity is 44ops/h; the max departure capacity is 52ops/h; the capacity of arrivals and departure by turns is 60ops/h.

Figure 3 shows the runways capacity contrastive curve of different operation mode. Curve $C_1$ shows the two parallel runways system capacity during independent operation. Curve $C_2$ shows the two parallel runways system capacity during of dependent approach and independent departure.
As shown in Figure 3, the capacity of dependent approach and departure operation mode compare to independent operation mode: the arrival and departure capacity correspondingly reduce, but the maximum of departure capacity isn’t changed; the reduction of arrival capacity is more obvious. The reason why capacity differentiates is that the aircrafts not only observe the minimum longitudinal separation between adjacent aircraft in the same final approach path but also observe the minimum lateral-diagonal separation between the aircrafts in adjacent final approach path. It results in increase in the minimum separation between successive aircrafts in the same final approach path. However, the departure process is all independent modes in the two cases, so the reduction isn’t too obvious.

6. CONCLUSIONS

The paper has developed the analytical capacity model from the point of view of controller’s actual works, and introduced the Shanghai Pudong international airport runways system capacity model of the two operation modes. The model has particularly considered the influence of the ATC minimum separation rules (longitudinal and lateral-diagonal), aircraft mix, the length of final approach path, buffer time and so on. Through the actually operation data, the paper estimates the Shanghai Pudong international airport runways system capacity. Also give the theoretic capacity curve for the two cases, and analyze the differences of the two cases.

REFERENCES

JIANG Bing, HU Ming-hua, TIAN Yong and HUANG Wei-fang.(2003) Further research of airport runway capacity evaluation. Journal of Traffic and Transportation Engineering,
Vol. 3, No. 2, 80-83.