Airport Capacity Analysis considering Terminal Air Traffic Flow Control and Airlines' Aircraft Sizing Behavior

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空港管制とエアラインの行動からみた空港容量拡大に関する研究

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わが国では航空需要の増加に対し，滑走路の新設等ハード面からの空港容量拡大によって対応してきており，管制方法やエアラインの行動の変化による容量増加等，ソフト面からの対策はあまり考慮されてきていない．本論文では，国内最大の混雑空港である羽田空港を対象として，容量拡大のための新たな管制方法とそれに対応した統計的容量算定方式の提案をし，さらに空港容量算定シミュレーションを活用し複数滑走路のインタラクションを考慮した容量拡大についても分析を行った．最後に，空港容量に大きな影響を与える機材構成について羽田空港再拡張後のエアラインの機材導入行動をモデル化し予測した．

1　Introduction

The demand of air transportation in Japan has increased steadily in recent years.　The airport capacity has been improved mainly by developing infrastructure such as runway expansions.　From the viewpoint of airlines, they have coped with the growth of air passenger demand by enlarging aircraft size.

In several foreign countries, airport capacity has been enhanced also by implementing flexible terminal air traffic control considering the aircraft size mix in addition to infrastructure improvements.　Aircraft characteristics such as runway occupancy time, separation minima are different for each aircraft size.　It is therefore important to consider these characteristics when considering airport capacity.　Many academic researches also focuses on how to improve the capacity by flexible air traffic control [(1)(2)(3)], but there are few researches of air traffic control for improving capacity in Japan.

With these backgrounds, first, this paper proposed a new method for calculating capacity corresponding to the flexible terminal flow control where the separation between two successive landing aircrafts is changed depending on the runway occupancy time (ROT) of the leading aircraft.　Secondly, the total capacity of HANEDA Airport after the new 4th runway construction (called re-expansion) was estimated by using the micro simulation [(4)] which can reproduce terminal air traffic flow in an airport with multiple runways when the several capacity enhancement scenarios were implemented.　Finally, airlines' aircraft sizing behavior after the expansion of HANEDA was analyzed since the aircraft mix in the future is also important for estimating capacity.

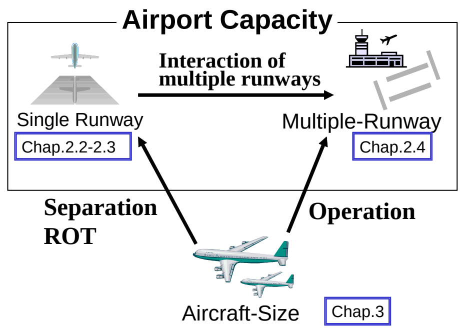

Fig.1 Relation of runway capacity and aircraft size

2　Airport capacity enhancement by flexible terminal air traffic flow control

2.1　The current calculation method of airport capacity in Japan [5)]

This section shows the current calculation method of airport capacity of HANEDA Airport by Ministry of Land, Infrastructure and Transport (MLIT).　In HANEDA, a takeoff and landing aircraft are basically operated separately in two runways before re-expansion. Since the runway capacity of landing is smaller than that of take-off, the total runway capacity is determined by the landing capacity (the number of landing and take-off aircraft should be the same).　Therefore, the runway capacity of landing is only shown below.

The runway capacity is basically determined by the larger separation shown below;

(a) The separation of the arrival aircraft in final approach（'Terminal radar control separation' or 'Wake turbulence separation'）,

(b) Runway occupancy time (ROT) which means the time duration of passing through runway threshold

to runway exit.
Here, (a) is currently defined as 120 seconds regardless of aircraft size mix, and (b) is defined as the sum of the three kinds of time duration as follows (also see Fig. 2).

①30.0 (sec): the passage time of the distance of 1(NM) before the runway threshold, which is the time duration required to direct Go-Around when the leading aircraft still remains in runway (t1);
② 79.5 (sec): time duration between the runway threshold and the runway lateral edge at exit, which is calculated by summing 60 seconds of average and 19.5 seconds (2.6 times of 7.5 seconds of standard deviation) (t2);
③15.0 (sec): time duration between the runway lateral edge (start point of exit-way) and stop line (end point of exit-way) (t3)
①+②+③= 124.5 (sec)

Since Time (a) < Time (b), the runway capacity of landing is 3600/124.5=28.9 28 (movements / hour). However, the latest declared capacity by MLIT is 30 (movements / hour) since t2 becomes 77 (sec) and t1 becomes 27 (sec) in the recent field survey of ROT in HANEDA.

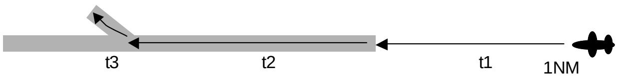

Fig. 2 Safe interval classification on runway of arrival aircraft

2.2 Proposal of a new terminal air traffic control and corresponding calculation method of capacity

In this section, we proposed a new flexible terminal flow control where the separation between two successive landing aircrafts is changed depending on the ROT of the leading aircraft. And we showed also the method for calculating capacity corresponding to the new air traffic control.

The exit position of an arrival aircraft which are A6 and A8 exit (see Fig.3) can be grasped in advance in general according to the aircraft size. Based on this premise, the separation of two successive landing aircrafts can be set 4-5NM when the leading aircraft is expected to use A6 exit (prior exit), and 6NM when the leading aircraft is expected to use A8 exit (secondary exit).

This flexible air traffic control enables shortening of variation of ROT which is considered for calculating Time 2 (t2, see 2.1) because the variation of inter-group (here, group means exit A6 and A8) can be ignored by taking the risk of its variation with different separation mentioned above.

The result of calculating the landing capacity based on this new method is shown in Table.1. The actual observed data of ROT of each exit were used for this calculation. The result shows that this new air traffic control can increase the capacity of 1 (movement/hour) comparing the current method.

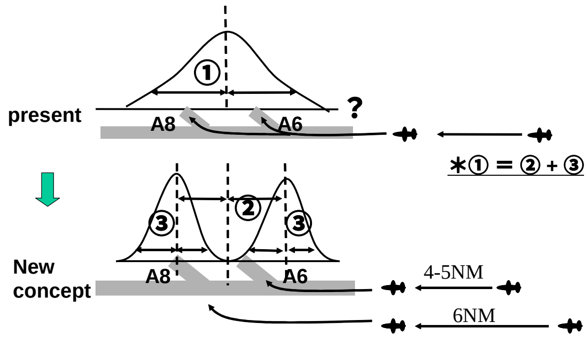

Fig.3 Concept of new terminal air traffic flow control

Table.1 Estimated runway capacity

New concept	ROT	Capacity/h
tt=w6(t1+t3+ EA6(t2)+c σ A6(t2))+w8((t1+t3+ EA8(t2)+c σ A8(t2)) =t1+t3+E(t2)+c(w6 σ A6(t2)+w8 σ A8(t2))	118.84	30.29
Present	**ROT**	**Capacity/h**
tt=t1+t3+E(t2)+c σ (t2)	122.66	29.35

2.3 Examination of flying separation in terminal area

If ROT is less than 120 (sec), it will become a bottleneck because the flying separation at terminal area is defined as 120 (sec) uniformly. However, the ROT with the proposed new air traffic control may be over 120 (sec). Therefore, we must consider also the capacity based on the flying separation at terminal area. According to the Air Traffic Control Standard, the separation is different depending on the combination of the size of successive aircrafts as shown in Table 2. However, in the present condition, management of the separation by the wake turbulence according to aircraft size is not performed. The flexible separation control might give the air traffic controller more workload. However, the flexible separation control is actually performed in several foreign countries such as Los Angeles international airport (LAX). Figure 4 shows the time separation of each aircraft size combination in LAX and HANEDA and Table 3&4 show the statistical test of the separation difference. From these results, we can see that LAX actually performs the flexible separation control. Therefore, HANEDA also has a potential to perform the flexible control although the current separation in HANEDA is uniform.

Average separation when considering the flexible separation control can be less than 120 (sec) because the separation after the medium size aircraft is around 90 (sec). Therefore it might not be the bottleneck to determine the capacity. However, the speed difference and the runway exit position depending on aircraft size are also necessary to consider all together. These factors are considered in the next section.

Table.2 Separation distance of wake turbulence

leading aircraft	following aircraft	separation(NM)
Heavy	Heavy	4
	Medium	5
Medium	Heavy	3
	Medium	3

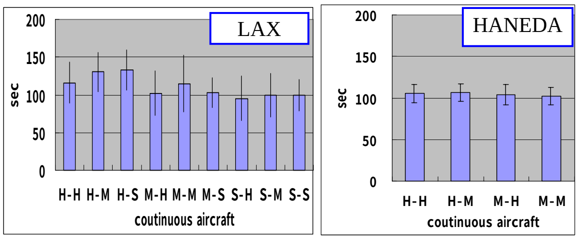

Fig.4 Separation time at runway threshold
（Los Angeles International Airport and Haneda）

Table 3 Result of t-test about time separation difference in Haneda airport

	H-H	H-M	M-H	M-M
H-H		P=0.56	P=0.48	P=0.28
H-M			P=0.29	P=0.18
M-H				P=0.59

Table 4 Result of t-test about t-test about time separation difference in LAX

P value	H-H④	H-M⑤	H-S⑥	M-H③	M-M③	M-S④	S-H③	S-M③	S-S③
H-H④	×	0.011**	0.031**	0.016**	0.841	0.015**	0.007*	0.005**	0.027**
H-M⑤	×	×	0.700	0.00*	0.002*	0.00*	0.00*	0.00*	0.00*
H-S⑥	×	×	×	0.00*	0.014**	0.00*	0.00*	0.00*	0.00*
M-H③	×	×	×	×	0.013**	0.862	0.323	0.553	0.665
M-M③	×	×	×	×	×	0.010*	0.007*	0.003*	0.03**
M-S④	×	×	×	×	×	×	0.252	0.418	0.571
S-H③	×	×	×	×	×	×	×	0.589	0.647
S-M③	×	×	×	×	×	×	×	×	0.996
S-S③	×	×	×	×	×	×	×	×	×

2.4 Estimation of capacity enhancement after HANEDA re-expansion by using air traffic simulation system

In this section, the estimation of the airport capacity of HANEDA with 4 runways (see Fig.5) is conducted by using air traffic micro simulation system developed by Hiramatsu (4). This simulation system can reproduce the microscopic behavior of landing and take-off aircraft at terminal air flow control area and it is already validated comparing with actual current capacity data. This system is very useful to estimate airport capacity because it can consider the interaction of multiple runways and can change aircraft behaviors easily. Fig.5 shows also the planned capacity after re-expansion by MLIT.

We first estimated the capacity when implementing the new air traffic control introduced in section 2.2 and 2.3. Secondly, we also designed the other two kinds of new air traffic flow control and estimated the capacity with those controls.

We hypothecated analysis scenarios as follow.

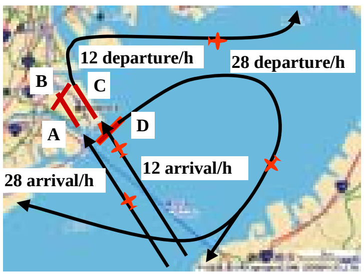

Fig.5 Arrival and Departure route after re-expansion in HANEDA

(0) Current operation (Base);
(1)Landing separation control considering leading aircraft's ROT which introduced in section 2.2&2.3 (A,B);
(2)Separation control of landing aircraft in C-runway for alternating control of landing in C-runway and take-off in each C- & D-runways (C). (Basically alternating control of landing and take-off might be most efficient in one runway, so the landing separation in C-runway is controlled based on the minimum separation required for take-off in C & D-runway between landing aircrafts of C-runway);
(3) Segregation of runway usage according to aircraft size (only small aircrafts (B737) A-runway landing and others landing to C-runway(D). (in scenario(2), the separation of landing aircraft in C-runway is larger than normal separation minima, so aircraft mix has almost no effect on capacity in C&D-runway. However landing of only small (medium) aircraft may have significant effect on capacity in A-runway;
(5) All (E).

Table.5 shows the results on each senario.

It was shown that the capacity of the airport increased by each scenario (also in Base case, because in MLIT plan there may be still unused capacity in C-runway). However, the number of landing aircrafts in A-runway became small. When separation control is adapted to C-runway, shortening of landing separation can prevent to take-off, and the number of landing aircrafts exceeds the number of take off aircrafts. It is necessary to decrease the number of landing aircrafts because it is assumed that the take off aircraft in the entire runway is made the same as the number of landing aircrafts. Therefore, the capacity of the runway decreases. Moreover, because scenario D and E are assumed that the share of small size aircraft (Medium) and large-size aircraft (Heavy) must be almost equal, it is necessary to an increase of the small size aircraft to enhance the capacity of the airport also in operation. Therefore, the trend of aircraft size mix in the future is also important for enabling abovementioned flexible air traffic controls. In the next chapter, we developed the model of aircraft purchase behavior by airlines and analyzed the future trend of aircraft size mix after re-expansion on HANEDA.

Table.5 Analysis senario and result of simulation

Senario		Milt plar	Base	A (1)	B (1)	C (2)	D (2+3)	E (1+2+3
(1): Separation Control considering Leading Aircraft's ROT		–	–	○(A&C)	○(A)	–	–	○(A)
(2): Alternating Control of Landing and Take-off in C-runway		–	–	–	–	○	○	○
(3): Segregation of Runway Usage according to Aircraft Size (medium aircraft in A-runway and heavy aircraft in C-		–	–	–	–	–	○	○
Estimated Capacity (movements / hour)	Landing in A-runway	28	30.3	31.1	31.2	30.2	31.0	31.5
	Landing in C-runway	12	18.6	13.6	18.6	19.6	19.6	19.4
	Take-off in C-runway	12	24.5	19.1	24.8	25.0	25.3	25.3
	Take-off in D-runway	28	24.8	25.6	25.1	25.1	25.5	25.7
	Landing -TOTAL	**40**	**48.9**	**44.7**	**49.8**	**49.8**	**50.6**	**50.9**
	Take-off - TOTAL	40	49.3	44.7	49.9	50.1	50.8	51.0

3. Model analysis of airline's aircrafts purchase behavior after HANEDA re-expansion

Officially, further expansion of the capacity of Haneda airport is scheduled in 2009. I conducted the model analysis of airlines' aircraft sizing behavior to understand the trend which airlines purchase and hold aircrafts after the expansion.

3.1 Model

We assume that there are two homogeneous airline industries in the market. Airlines seek to maximize the net present value over 20 years. The timing of decision of airline is year 2007, by which I take into account the duration for the education of pilot and time lag between order and delivery of aircrafts. I also assume that airlines have the two options for purchasing aircrafts. The first option is carried out in 2009 when Haneda Airport will be re-expanded. The second option is exercised in 2014, five years' later of Haneda's re-expansion. Except for these two timings, airlines can neither purchase aircrafts nor increase flight volume. All purchased aircrafts are used for service.

I assume that the three strategies of airlines for purchasing aircrafts for simplification.

1. Purchasing large-sized aircrafts
2. Purchasing small-sized aircrafts
3. Deferring purchase for aircrafts

When airlines purchase new aircrafts, they will decide the number of purchased aircrafts so that they can ship ten million passengers per year. I set the number of seats of large-sized aircrafts is 400 people assuming they are B747 or B777, while those of small-sized aircrafts are 100 people assuming that they are B737 or RJ.

Annual average Load Factor (LF) is fixed to be 70%. When the traffic volume which will be assigned by logit-based passenger demand model exceed the number of offered seats in the future, airlines' will choose one of the following two options: (1) changing small-sized aircrafts to large-sized aircrafts; (2) abandoning the excess demand (which will assumed to shift to other travel modes).

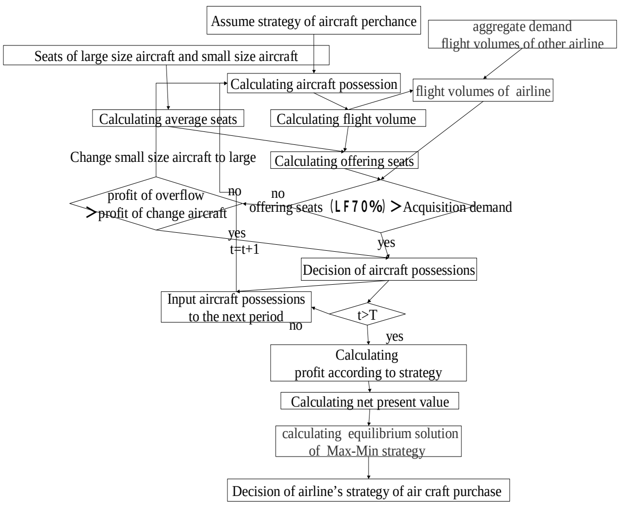

Fig.6 Algorism for calculating airlines' profit

3.2 Numerical Simulation

Each airline decides the type and the number of purchased aircrafts. Finally, their owned aircrafts and profit will be calculated for each time period. This takes the form of a strategic game between competitive two airlines and they will decide the optimal strategy according to their profit. The detailed procedure for this is shown in Fig.6. Parameters for numerical simulation are not shown due to limited space.

Fig.8 shows the equilibria (i.e. the combination of Max-Min strategies) in two-person game for several situations. For the case where the expansion of HANEDA will be conducted only in 2009 (single expansion), the solution of the game is purchasing small-sized aircrafts for each airline for each stage, while Pareto optimality in this game is pass up at first stage and purchase large-sized aircrafts at second stage. It implies that unless two airlines try to purchases their aircrafts in cooperation with each other, airline operate highly-frequent career service with small-sized aircraft in order not to lose share of slot to competitors. On the other hand, if airlines behave cooperatively, airlines operate large-sized aircrafts with low cost per seat mile, and with low frequency in response to demand increases, keeping mint slots.

Now, we assume that the expansion of HANEDA will be conducted at two-steps and the slots for airlines are released 2 times. Fig.8 also shows the Max-Min solution for such situation: purchasing large-sized aircrafts at the first step and choosing small-sized aircrafts to buy at the second. This solution is also in pareto optimality. It implies that if the government increases the airport capacity by slow degrees, airlines tends to upsize their aircrafts in earlier stage.

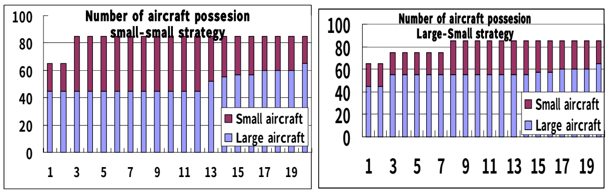

Fig.7 Number of aircraft possession

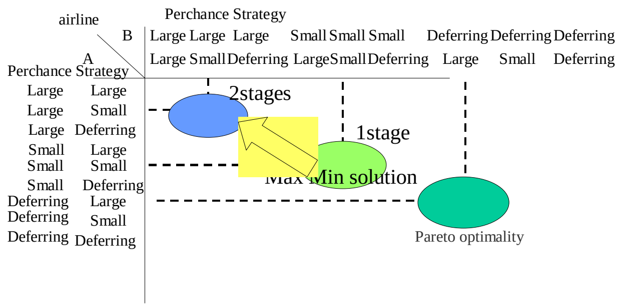

Fig.8 Optimal strategy

4 Conclusion

The result of this research is the following two points.

- The new terminal air traffic controls for enhancing the capacity were proposed.
- The future aircraft size mix after HANEDA re-expansion was analyzed by modeling airline's aircraft purchasing behavior.

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