Hub Dominance and Runway Capacity Constraint in Air Cargo Transport Markets: Model Analysis

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Abstract:
This paper discusses the theoretical framework for considering network design and choice of aircraft size in order to understand the hub dominance in the air cargo transport markets. The model is a bi-level market model that is constructed by air carriers' behavior as leader, and shippers' behavior as follower. We assume the duopoly market in which air carriers aim to maximize their profit by designing shipping network. Shippers aim to reduce their generalized shipping cost which consists of shipping time, waiting time, tariff and monetary value of congestion. We assume that the equilibrium flow of commodities is given as stochastic user equilibrium flow. Computation results suggest that the carrier which holds the dominant hub airport rules the market but the hub dominance is unstable. Hub dominance heavily depends on the balance between runway capacity and local cargo flows.

Key Words: Air Cargo Market, Duopoly, Hub-Spokes Network

1. INTROUCTION

Although we are now afraid of the global economic recession, the air cargo transport market is still growing steadily. For example, the trans-Pacific air cargo market is still growing two to three percent per year. This steady growth is considered to affect the network construction of cargo transport. Incheon Airport of Seoul is one of the biggest international cargo hub airports and Chek Lap Kok of Hong Kong acts as the world leader of air cargo handling. Big integrators such as FedEx and UPS build their main hub in Mainland China for Eastern Asia transport. Appearance of the big hub airports in Mainland China is anticipated to make a big impact on Eastern Asia cargo transport markets. These airports will be mega hub airports and they occupy the dominant position in terms of handling connecting cargos, and, therefore, one may say that "these big hub airports dominate the air cargo markets" in the Eastern Asia. However, in the western world, many major hub airports, such as Chicago O'Hare and Frankfurt, suffer from congestion but it is difficult to expand runway capacity at these airports because of the huge cost of expansion. Then, Asian major airports will suffer from shortage of runway capacity due to their rapid economic growth. Other airports such as Kansai Airport of Osaka and Taoyuan Airport of Taipei should seek the way to survive this serious situation, because they do not have so much local cargo volume as Chinese airports have. Thus, the key to survive as hub airport is to understand the nature of competition in order to collect connecting cargos, and the key factors for that would be "hub location" and "network competition."

The hub-spokes network design problem, sometimes known as "hub location problem," has been addressed for almost thirty years, and some of well-known works in this research area are the works of O'Kelly (1987), O'Kelly et al. (1996), and Campbell (1996). They mainly discuss the single assignment hub-spokes network system and formulate this network design problem as the p-hub median problem. They discuss one carrier's network design problem as the cost minimization problem. However, carriers usually face the competition with rivals, and their network design strategy on deciding hub location, frequency, and aircraft size, should depend on the competition. Adler and Smilowitz (2007) propose the airfare setting and hub location problem with the merge partner search problem. Their work is probably a first work that discusses the hub location problem considering market share, but they do not deal with the "network design" itself which is dealt in Adler's previous works (Adler, 2001, 2005). Thus, the relation among hub location, aircraft size, level of service (frequency) relating to shipping cost and market share is still unclear.

Research of the competition in air transport market also has a long history. In the last two decade, many articles address this issue, such as Brander and Zhang (1990), Oum et al. (1993), and Hendricks et al. (1999). However, most of them focus on carriers' behavior; they neglect user's behavior. Competition through the transport network is supposed to be affected by user's behavior. Thus, some supply-demand interaction models are proposed (Hong and Harker (1992), Adler (2001, 2005), Takebayashi (2005, 2008)). These interaction models try to express user's behavior as well as carrier's behavior, and in these models, the idea of equilibrium is sometimes assumed (Adler, 2005; Takebayashi, 2008). Unfortunately, these articles do not discuss the behavior of equilibrium solution. Furthermore, these researches do not deal with the effect of physical constraints such as runway capacity from the theoretical point of view, though physical constraints are thought to play an important role for designing the network and attracting the connecting flows, which should be especially important for understanding the hub dominance.

This paper proposes the computable model for understanding the relation among hub location and network competition from the theoretical point of view and analyzes the mechanism of hub dominance in air cargo transport markets.

2. THE MODEL

2.1 Outline

In this paper, the model is developed based on the bi-level air transport market model (Takebayashi, 2008). The improved point is that the model can handle airlines' strategy of both determination of flight frequency and choice of aircraft size, compared with the formerly proposed model which assumes that airlines' strategy is to control flight frequency.

The basic type of bi-level air transport market model is a class of Stackelberg game and the model assumes airlines as leaders and passengers/shippers as followers. The detail information is described in the former paper (Takebayashi, 2008), so that let us show the structure of basic model and describe the improved points. The basic assumptions are as follows:

(1) The total volume of OD demand is predetermined and fixed.
(2) Each aircraft is a freight aircraft. We do not deal with the berry cargo transport.
(3) Each aircraft has a limited space for cargos. Thus, we assume the capacity constraint on each aircraft.
(4) The airports which are used as hub airports are assumed to have the runway capacity constraint.

Since we consider the congestion of both airport and flight to comprehend the nature of air cargo transport in the busy market, we assume (3) and (4).

2.2 Shippers

In this paper, we deal with the behavior of individual shippers. In the real world, shippers usually use forwarders for cargo shipping. However, it is difficult to have the credible information about shippers' choice of forwarders and there is no information about forwarders' route choice behavior. Thus, we focus on the behavior of individual shippers.

We assume the following interaction structure between shippers and air carriers: Each carrier gives the detail information about routes to the shipper and the shipper chooses the best available route . Under this assumption, when choosing the best route, shippers compare disutility of each route of which information consists of shipping duration, shipping costs, connectivity and congestion. Shipping duration includes access and egress time between a centroid and an airport and line haul time, shipping cost includes access and egress fee and airtariff, and connectivity is expressed by flight frequency in each OD market.

Since we deal with fixed demand for cargo allocation, OD volume should be conserved. Bell (1995) firstly points out that the Stochastic User Equilibrium (SUE) with bottleneck allocation problem can be rewritten as the equivalent optimization problem. Since the original model is given as the link-based formulation, our model is rewritten with the route-based formulation. The general formulation of SUE with bottleneck is given as follows:

[Shippers' Route Choice Behavior: Cargo Allocation Problem]

$$Object: \Gamma(x_k^{rs}) = \frac{1}{\theta} \sum_{rs \in \Omega} \sum_{k \in K^{rs}} x_k^{rs} (\ln x_k^{rs} - 1) + \sum_{rs \in \Omega} \sum_{k \in K^{rs}} u_k^{rs} x_k^{rs} \to \min \tag{1}$$

Subject to

$$\sum_{k \in K^{rs}} x_k^{rs} = X^{rs}, for \, \forall rs \in \Omega \ , \tag{2}$$

$$x_{l^n} = \sum_{rs}\sum_{k} x_k^{rs}\delta_{l^n}^{rsk} \le v_{l^n} f_{l^n},\ for\ \forall l^n \in I^n, \forall n \in N, \tag{3}$$

$$x_k^{rs} \ge 0,\ for\ \forall k \in K^{rs}, \forall rs \in \Omega, \tag{4}$$

where θ is a predetermined distribution parameter in SUE; *rs* means the OD pair, origin *r* to destination *s; Ω* means a set of OD pairs; *k* is a service route in *rs* OD market; K^{rs} is a set of service routes provided for *rs* OD market; x_k^{rs} means a commodity flow from *r* to *s* on route *k*; u_k^{rs} means disutility of shipper who use route *k* of *rs* OD market for shipping without congestion; X^{rs} is a OD volume of *rs* OD market; l^n means a commercial link operated by carrier *n*; I^n is a set of links operated by carrier *n*; x_{l^n} means a commodity flow of link *l* operated by carrier *n*; v_{l^n} means an aircraft size on link *l* operated by carrier *n*; $\delta_{l^n}^{rsk}$ is a dichotomous variable that takes one when *k*th route in *rs* OD market on link l^n, otherwise it takes zero; *N* means a set of carriers.

Equation (1) is the object function of OD shippers and the first term of the right-hand side shows the entropy term. Constraint set (2) is same as Bell's formulation. Constraint set (3) is link flow capacity constraint which consists of aircraft size v_{l^n} and flight frequency f_{l^n}.

Since congestion cost due to link flow capacity constraint is included in shipper's disutility function U_k^{rs}, it is strictly treated as a convex function. The disutility function of shipper choosing route *k* of *rs*, which consists of deterministic costs, is defined as linear function:

$$u_k^{rs} = t_k^{rs} + \alpha_1 p_k^{rs} + \sum_{l \in I} \frac{\alpha_2}{f_l}\delta_l^{rsk}, \tag{5-1}$$

where p_k^{rs} is the airfare, t_k^{rs} is a travel time, and f_l is a service frequency in link *l*. α_1 and α_2 are parameters. The third term of right-hand side means average waiting time derived from service frequencies. We suppose that shippers are sensitive to convenience and they consider the average waiting time, which expresses the connectivity, as a part of travel cost. Finally, shipper's disutility function including congestion cost, U_k^{rs}, is described as

$$U_k^{rs} = u_k^{rs} + \sum_{l}\left(\lambda_l\right)\delta_l^{rsk}, \tag{5-2}$$

where λ_l is the congestion cost in link l, which is obtained as Lagrange multiplier relating to constraint set (3). Meanwhile, link *l*'s congestion cost λ_l is obtained as a value of Lagrange multiplier reflecting the activity of constraint set (3).

2.3 Carriers

Each carrier is assumed to maximize its profit by controlling the flights in each OD market. Each carrier's control variable is flight frequency f_{l^n} and its aircraft size v_{l^n}. Operation cost per flight in link l^n, $C_{l^n}^{OP}$, is given independently. For simple understanding, we neglect fixed cost.

Carrier n's profit maximization problem by controlling both f_{l^n} and v_{l^n} is expressed as follows:

[Carrier's Profit Maximization Problem]

$$Object: \pi^n(f_{l^n \in I^n}, v_{l^n \in I^n}, \tilde{f}_{l^{-n} \in I^{-n}}, \tilde{v}_{l^n \in I^{-n}}) = \sum_{rs}\sum_{k} p_k^{rs} \hat{x}_k^{rs} \delta_n^{rsk} - \sum_{l \in I^n} C_{l^n}^{OP}(v_{l^n}) f_{l^n} \to \max, \quad (6)$$

subject to

$$f_{l^n} v_{l^n} \geq x_{l^n} = \sum_{rs}\sum_{k} \hat{x}_k^{rs} \delta_{l^n}^{rsk}, for \forall l \in I^n, \quad (7)$$

$$\sum_{l^n} f_{l^n} \delta_{l^n}^h \leq F_h^n \quad for\ \forall h \in H, \quad (8)$$

$$f_{l^n} \geq f_{LOW}, for \forall l^n \in I^n, \quad (9)$$

$$v_{l^n} \in v_{type}^n, \forall l^n \in I^n, \quad (10)$$

$$\begin{aligned} \hat{x}_k^{rs} &= \arg\{\min : \Gamma(x_k^{rs})\ subject\, to\, (2)\, to\, (4)\}, \\ & for \forall k \in K^{rs} \quad and \quad rs \in \Omega \end{aligned}, \quad (11)$$

where $\hat{x}_k^{rs}$ means the optimal flow of route k in rs OD market; δ_n^{rsk} is a dichotomous variable that takes one when kth route in rs OD market is operated by carrier n, otherwise it takes zero.

Constraint set (8) means runway capacity constraints for carrier n. F_h^n is runway capacity for carrier n at airport h; $\delta_{l^n}^h$ dichotomous variable that takes one when link l^n includes airport h and otherwise takes zero. In constraint set (9), f_{LOW} means minimum required frequency. In the computation, it is given as a small real number ε. v_{type}^n means the set of aircraft type that carrier n has. $\Gamma(x_k^{rs})$ means an optimal value function for shippers' route choice behavior.

Object function (6) consists of revenues (first term), and costs (second term). Constraint set (7) expresses that each cargo flow does not exceed the available space. Constraint set (8) means general constraints for flight frequency. Constraint set (9) is a nonnegative constraint for f_{l^n} . Constraint set (10) means that carrier n should choose the aircraft type from the variation of its own stock. Constraint set (11) shows cargo flow defined as the best response function to carriers' behavior. x_k^{rs} can be obtained as a solution of SUE.

2.4 Obtaining the Sub-game Perfect Solution of Carriers Competition

Since Carrier's profit maximization problem is formulated as the problem with two types of control variables which are dependent each other, it is tough to solve directly; this problem is classified as the non-convex problem. But, to consider the structural conditions of air transport market may bring the reduction of computation volume. Usually, the variety of aircraft types is much less than the variety of service frequencies. Since the bi-level market model which can analyze carriers' strategy on service frequency as floating point computation is already developed, we deal with this problem as the combination of integer programming problem for aircraft type determination and network design problem.

For obtaining the solution, we adopt the two-stage game framework. In the first stage, carriers choose aircraft size for each leg; in the second stage, they design their network. If this game has a unique solution, it is regarded as the unique Nash equilibrium.

3. NUMERICAL EXAMPLES

In this section, we discuss the characteristics of developed model and discuss some situations from the theoretical point of view. To avoid the computational complexity, we deal with the duopoly case in the following computations.

We consider the relation between network shape and Nash equilibrium. We discuss the characteristics of competition between different network shapes through some numerical computations.

3.1 Market Conditions

In the following numerical computation, we set market conditions as below:

1) We consider duopoly market: there are two carriers in the market.
2) The target area consists of five zones and each zone has one airport. Each OD shipper can use its local airport as an origin/destination airport.

3) The shape of service network is predetermined and fixed.
4) Each OD airfare is predetermined and fixed.
5) We consider the single assignment hub-spokes system.
6) Each carrier chooses an aircraft type: type A (100-space) or type B (200-space).

We set two types of network. Both are single assignment hub-spokes network systems, but in the scenario studies, carrier 1 adopts type 1 network (Figure 1) and carrier 2 adopts type 2 network (Figure 2). Connecting air cargos are transferred at hub airports. Parameters of shipper's disutility function are given as α_1=0.74, α_2=10.1 and distribution parameter is given as θ=0.26. Network conditions are listed in Table 1. We assume markets relating to airport 3 are major markets.

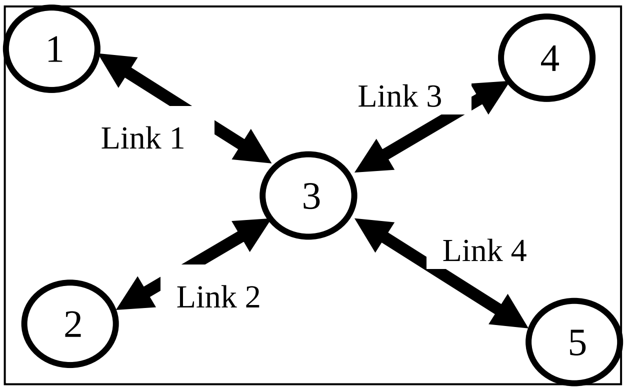

Figure 1 Single-hub system (type 1)

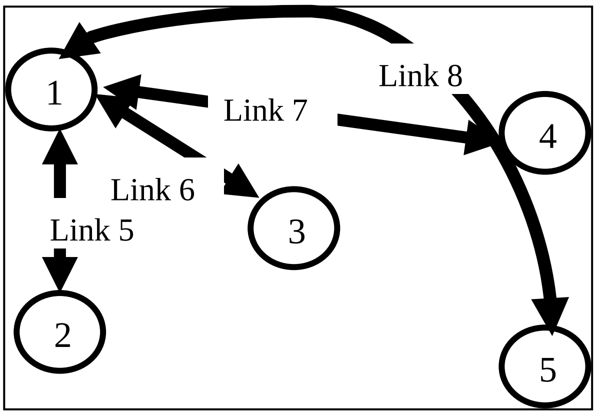

Figure 2 Single-hub system (type 2)

Table 1 OD traffic flow, market distance, linehaul time, and airfare

	1	2	3	4	5
1	0	200 (500) <90> [25]	300 (500) <90> [25]	200 (1000) <180> [50]	200 (1000) <180> [50]
2	200 (500) <90> [25]	0	2000 (500) <90> [25]	1000 (1000) <180> [50]	1000 (1000) <180> [50]
3	300 (500) <90> [25]	2000 (500) <90> [25]	0	2000 (500) <90> [25]	2000 (500) <90> [25]
4	200 (1000) <180> [50]	1000 (1000) <180> [50]	2000 (500) <90> [25]	0	1000 (500) <90> [25]
5	200 (1000) <180> [50]	1000 (1000) <180> [50]	2000 (500) <90> [25]	1000 (500) <90> [25]	0

Note: No-bracket values show OD flows. Values in ( ) show market distance. Values in < > show linehaul time. Values in [ ] show OD airfares.

We assume that the marginal cost for operating large size aircrafts is smaller than that for small size aircrafts because of the economy of scale. Thus, we set that the marginal cost for type B is 5% less than that for type A, i.e., 0.030 and 0.0315, respectively. We assume two classes of airfare for OD markets: 50 for long haul markets (1-4, 1-5, 2-4, and 2-5) and 25 for short haul markets (others). The initial frequency given to each link is three.

We set 16 strategies, for example, strategy 1 is “type A aircraft for all legs” or strategy 16 is “type B aircraft for all legs,” for each carrier. Henceforth, we express the strategy combination of Carrier 1 and 2 as (Carrier 1, Carrier 2). For example, (1, 16) means that Carrier 1 choose strategy 1 and Carrier 2 choose strategy 2. The strategies are listed in Table 2.

3.2 Hub Dominance and Capacity Constraint

Firstly, let us check the basic behavior of the model. Both carriers use airport 3 as their hub airport. We carry out computations with different runway capacity constraints: 30, 40, 50 flights, and unlimited flights for each carrier. As a result, we find that reduction of runway capacity constraint leads to downsizing of aircraft (Table 3). For example, under 30 flights limitation, the optimal strategy set is (8, 8), i.e. “type B aircraft for all legs except market 1-2” and under the condition of no runway capacity constraint, the optimal strategy set is (2, 2). Thus, we can say that when the runway capacity is fully relaxed, both carriers are expected to adopt strategy 2 as the optimal strategy, i.e. they mainly use small aircrafts. On the other hand, when the runway capacity constraint becomes severe, both carriers prefer to operate larger size aircrafts. This response seems to fit carrier’s response in the real markets.

Results show another interesting point. When the runway capacity is relaxed, the flow of connecting cargos increases (shown in brackets in Table 3).

Table 2 List of strategies

No. of Strategy	combination	No.	combination	No.	combination	No.	combination
1	A, A, A, A	5	A, B, A, A	9	B, A, A, A	13	B, B, A, A
2	A, A, A, B	6	A, B, A, B	10	B, A, A, B	14	B, B, A, B
3	A, A, B, A	7	A, B, B, A	11	B, A, B, A	15	B, B, B, A
4	A, A, B, B	8	A, B, B, B	12	B, A, B, B	16	B, B, B, B

Note: type of aircraft is listed as (link 1 (5), link 2 (6), link 3 (7), link4 (8)).

Meanwhile, in Link 4 which covers large volume of connecting cargos of market 2-4 and 2-5, both economy of scale and economy of frequency¯the marginal revenue increases in proportion to frequency—are supposed to work. In other words, if there is a market where both economy of scale and economy of frequency work, downsizing of aircraft does not appear and carriers still use large size aircrafts. On the contrary, under the severe runway capacity constraint, economy of scale and economy of frequency do not work together; economy of scale works more strongly in many markets and economy of frequency becomes weaker and disappears.

Table 3 Basic behavior of the model: runway capacity constraint (hub: Airport 3)

capacity	strategy	airline 1/2 freq	cargo flow
30	8	2.0, 4.8, 4.1, 4.1	5484 (7.6)
50	4	2.6, 9.4, 6.5, 6.5	6176 (598.1)
no const.	2	3.8, 12.1, 13.3, 6.7	6286 (757.2)

Next, let us discuss the competition between carriers which adopt different types of hub-spokes network. We set the case where Carrier 1 adopts type 1 network and Carrier 2 adopts type 2 network. In type 2 network, its hub airport, airport 1, is assumed to have no runway capacity constraint while airport 3 of type 1 network has different runway capacity constraint by case. The results are listed in Table 4.

Table 4 Competition between Different Shapes of Network

	airline 1			airline 2		
capacity	strategy	freq	cargo flow direct (connect)	strategy	freq	cargo flow direct (connect)
no const.	8	3.5, 9.9, 11.3, 11.3	12214.5 (611.3)	1	3.2, 3.5, 2.8, 2.8	1082.4 (159.2)
70	8	3.2, 9.9, 10.9, 10.9	12191.4 (458.6)	1	3.2, 3.5, 2.8, 2.8	1093.1 (177.0)
60	16	1.1, 8.8, 10.0, 10.0	11480 (106.6)	1	3.1, 3.6, 2.8, 2.8	1273.3 (340.0)
50	8	1.5, 6.7, 8.4, 8.4	9583.9 (1.5)	9	1.7, 4.5, 2.5, 2.5	1209.8 (607.3)
40	16	0.1, 6.4, 6.8, 6.8	8005.5 (0.2)	5	3.4, 2.9, 3.1, 3.1	1394.7 (802.3)
30	8	1.4, 4.7, 4.4, 4.4	5676.4 (0.03)	5	3.2, 2.7, 3.1, 3.1	1162.4 (906.4)

Table 4 shows the obvious change in terms of hub dominance. In the case of no runway capacity constraint at Airport 3 (listed at the top of Table 3), Carrier 1 of which base is Airport 3 is a dominant cargo carrier and the cargo flow connecting at Airport 3 is much larger than the cargo flow connecting at Airport 1. Since local cargo flow at Airport 3 is much larger than the local cargo flow at Airport 1, Carrier 1 can collect a large volume of local cargos. And then, this large local cargo flow attracts more connecting cargo flow due to the effect of combination of economy of frequency and economy of scale. This positive feedback loop is regarded as the effect of increasing returns to scale. As a result, the strong effect of increasing returns to scale makes Airport 3 as the dominant hub airport.

Table 4, however, also shows that dominance of Airport 3 is not stable; it is sensitive to the market condition. In order to understand the relation between the volume of local cargo flow and runway capacity, we carry out the sensitivity analysis on runway capacity constraint. When the runway capacity at Airport 3 decreases in spite of the large volume of local cargos, the capacity constraint becomes stricter. The effect of economy of frequency of Carrier 1 becomes limited, and then Carrier 1 should reduce its service frequency. Furthermore, when the shortage of runway capacity becomes serious and reaches to the certain level--bifurcation, the hub dominance of Airport 3 rapidly deteriorates: the volume of connecting cargos at the "major" hub airport drastically decreases, and as a result, it loses its big share of connecting cargos.

This bifurcation gives us the following suggestion. Since the runway capacity constraint is regarded as the shortage of runway capacity compared with the volume of local cargo flow, the combination of runway capacity and the local cargo volume is expected to play an important role for hub dominance.

On the other hand, Carrier 2 gains more cargos connecting at Airport 1. Airport 1 has much less local cargos than local cargos at Airport 3. Thus, Airport 3 has enough capacity for both local and connecting cargos, while the congestion of flights operated by Carrier 1 becomes more serious. And then, shippers switch their optimal routes from the routes of Carrier 1 to the routes of Carrier 2. However, the volume of connecting cargo using Airport 1 increases too much, the local cargo flow is depressed and the total cargo volume decreases.

From these results, we have some suggestions about the competition between hub airports of different network:

1) If the hub airport which has a big volume of local cargos— we say "major airport"— has enough runway capacity for both local and connecting cargo flows, this type of hub airport can collect many connecting cargos and it works as a dominant hub in the area.
2) However, if the major hub airport faces a serious shortage of runway capacity for its large volume of local cargo flows, the dominant hub airport loses its share. Conversely, the

rival small hub airport can increase its connecting cargo flows.

3) The balance of runway capacity and local cargo volume probably plays an important role for hub dominance.
4) When the major hub has no runway capacity constraint, the carrier using the major airport as its hub tends to adopt “large aircraft with frequent flight” strategy. Under the serious runway capacity constraint at the major hub, the carrier still operates large size aircrafts. On the other hand, the rival carrier basically operates small size aircrafts.

Generally, we believe that the airport which has large volume of local cargos will become the hub airport in the area and this corresponds to Suggestion 1. And Suggestion 1 fits the finding in former researches. However, Suggestion 2 and 3 tell another future. If runway capacity shortage occurs at the major hub airport, connecting cargos shift their routes to less-congested airports and the hub dominance in the area will change. Suggestion 4 is a new one which is not discussed in the former researches.

4. CONCLUSION

This paper proposes the enhanced bi-level air transport market model which can handle both network design and determination of aircraft size problem. Computation results tell that the chance to have a position of hub remains for currently minor airports. However, it still depends on the condition of currently major airports. Finally we find that the key for understanding the hub dominance is the balance of runway capacity and local cargo flows.

Our main outcomes suggest that the carrier of which base airport has a small volume of local cargos can act as a “connecting” hub when the major hub airport is congested and faces a serious shortage of runway capacity. In this case, shippers refuse to use connecting routes via congested major hub airports and prefer to use connecting routes via small but not congested airports.

From our outcomes, we can have a suggestion for the actual airport management as follows:

Our results suggest if the congestion due to the shortage of runway capacity becomes more serious in the major hubs and the major carriers cannot change their hub location, some other carriers may change their network design strategy for improving their competitiveness. They shift to other not-congested airports and change the shape of their network with frequent flights of small aircrafts. And most importantly, our results suggest that these two different types of network can exist together. This suggestion implicates that various network services based on different network design strategies can survive in the busy cargo transport markets, if the issue of runway capacity constraints becomes very serious in the markets. Thus, other airports that currently do not work as major hubs will have a chance to survive in the markets if they invite these carriers.

We will apply the developed model to the real cargo transport markets and evaluate the competitiveness of Asian airports in the future research.

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